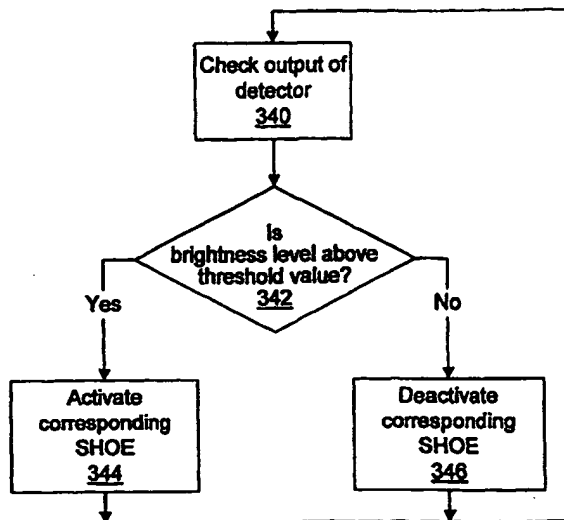




## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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<b>(21) International Application Number:</b> PCT/US99/24158  <b>(22) International Filing Date:</b> 15 October 1999 (15.10.99)  <b>(30) Priority Data:</b> 60/104,609      16 October 1998 (16.10.98)      US  <b>(71) Applicant (for all designated States except US):</b> DIGILENS, INC. [US/US]; 306 Potrero Avenue, Sunnyvale, CA 94086 (US).  <b>(72) Inventor; and</b> <b>(75) Inventor/Applicant (for US only):</b> POPOVICH, Milan, M. [GB/GB]; 53 Westfield Road, Leicester, Leicestershire LE3 6HU (GB).  <b>(74) Agent:</b> STEPHENSON, Eric, A.; Conley, Rose & Tayon, P.C., Suite 320, 816 Congress Avenue, Austin, TX 78701-2443 (US).		<b>(81) Designated States:</b> AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).  <b>Published</b> <i>With international search report.</i>

**(54) Title:** SWITCHABLE HOLOGRAPHIC FILTER FOR BRIGHT LIGHT SUPPRESSION

**(57) Abstract**

An apparatus and method is described for suppressing bright lights using holographic techniques. The apparatus includes a plurality of switchable holographic elements (SHOE), a plurality of detectors, and a processing circuit coupled to the SHOE and detectors. Each SHOE has a field of view. For each SHOE there may be a corresponding detector that has a field of regard that covers substantially the same points as the corresponding field of view. When a light from a bright source is incident on a detector, the detector outputs a signal to the processing circuit. The processing circuit activates the corresponding SHOE thereby diffracting a portion of the light incident on the SHOE away from a viewer. When no light is incident on a detector, the processing circuit deactivates the corresponding SHOE thereby allowing all light incident on the SHOE to be transmitted through the SHOE without substantial alteration. The SHOE may be formed from a polymer dispersed liquid crystal material.

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**TITLE: SWITCHABLE HOLOGRAPHIC FILTER FOR BRIGHT LIGHT SUPPRESSION****BACKGROUND OF THE INVENTION**

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**1. Field of the Invention**

The present invention generally relates to light attenuation, and more particularly to an apparatus and method for automatic bright light suppression using switchable holograms.

10 **2. Description of the Relevant Art**

People's eyes and sensitive devices often need to be protected or shielded from bright lights. A sufficiently bright light may make it difficult for a person to see and in extreme cases may cause permanent damage to the eyes. For example, the driver of a vehicle or the pilot of an aircraft or watercraft may need to shield their eyes from the sun during the day and from the headlights of other vehicles during the night. Protection from bright lights is particularly important when using optical devices that magnify such as binoculars or gun sights. If a bright light source is accidentally viewed, permanent damage to the eyes may result due to the additional light gathering power of the magnification device. Laser provide an extremely bright source of light that can be particularly damaging if accidentally viewed. Laser operators typically need to wear some form of eye protection. If a device, such as a charge-coupled device ("CCD") or photomultiplier, is used to detect light, exposure to a sufficiently bright light source may damage or destroy the device.

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A typical form of protection involves suppression of bright lights by placing a filter, which transmits only a fraction of the incident light, between the light source and the viewer. For example, drivers of vehicles often wear sunglasses or the windows of the vehicles may be tinted. One of the optical elements in a pair of binoculars may be coated to reduce the amount of light transmitted through the binoculars. Laser operators often wear glasses or goggles that transmit little or no light at the operating wavelength of the laser. Such forms of bright light suppression attenuate light regardless of the brightness of the light or, in other words, both bright light sources and dim light sources are attenuated. For example, although sunglasses may attenuate the brightness of the sun, they also make it more difficult for a driver to see in the shade or at night. This may be extremely distracting to a driver when brightness levels are rapidly changing.

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It is therefore desired to develop an improved apparatus for suppression of bright light and not attenuating lower light levels. It is further desired that the amount of attenuation of a bright light depends on the intensity of the light. It is also desired if the attenuation of a light source may be rapidly changed in response to variation in the intensity of the light.

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**SUMMARY OF THE INVENTION**

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The problems outlined above are in large part addressed by an apparatus in which a switchable holographic optical element (SHOE) automatically adjusts its transmittance in response to a bright light. The SHOE may always attenuate a bright light above a predetermined threshold value by a set amount or the amount of attenuation may depend on the intensity of the bright light. By automatically adjusting its transmittance in response to a bright light, a SHOE may advantageously protect the eyes of a person looking through the SHOE

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from bright lights while simultaneously still allowing the person to have good visual acuity when bright lights are absent. Although any type of SHOE may be used, the SHOE is preferably a Bragg hologram comprising a polymer dispersed liquid crystal material. A Bragg hologram is preferred due their high diffraction efficiency. A switchable Bragg hologram fabricated using a polymer dispersed liquid crystal material is further preferred due to their fast switching rate, low switching voltage, and high diffraction efficiency. A fast switching rate allows the SHOE to respond quickly to rapidly changing lighting conditions, a low switching voltage reduces demands placed on the electronics required to operate the SHOE, and a high diffraction efficiency allows the SHOE to effectively attenuate bright lights.

One embodiment of the apparatus to attenuate bright lights includes a plurality of SHOEs, a plurality of detectors, and a processing circuit coupled to the SHOEs and the detectors. Each SHOE has a field of view corresponding to the angular bandwidth of the hologram. When activated, the SHOE diffracts light incident on the SHOE within its angular bandwidth away from a viewer. When deactivated, the SHOE transmits light incident on the SHOE without substantial alteration. The field of views of the SHOEs may be unique or adjacent field of views may partially overlap. Each SHOE may have a corresponding detector. A field of regard of the detector is such that the detector sees substantially the same points in space as its corresponding SHOE. The SHOEs may be stacked together or may be tiled next to one another. The processing circuit monitors the output of the detectors and activates and deactivates the SHOEs.

In addition to the apparatus described above, a method is contemplated herein. The processing circuit checks the output of each of the detectors either simultaneously or sequentially. If light incident on the detector exceeds a predetermined threshold value, the circuit activates the corresponding SHOE by applying a first voltage to the SHOE. If light incident on the detector does not exceed a predetermined threshold value, the circuit deactivates the corresponding SHOE by applying a second voltage to the SHOE.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

Other objects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the accompanying drawings in which:

FIG. 1 is a cross-sectional view of an electrically switchable hologram made of an exposed polymer dispersed liquid crystal (PDLC) material made in accordance with the teachings of the description herein;

FIG. 2 is a graph of the normalized net transmittance and normalized net diffraction efficiency of a hologram made in accordance with the teachings of the description herein (without the addition of a surfactant) versus the rms voltage applied across the hologram;

FIG. 3 is a graph of both the threshold and complete switching rms voltages needed for switching a hologram made in accordance with the teachings of the description herein to minimum diffraction efficiency versus the frequency of the rms voltage;

FIG. 4 is a graph of the normalized diffraction efficiency as a function of the applied electric field for a PDLC material formed with 34% by weight liquid crystal surfactant present and a PDLC material formed with 29% by weight liquid crystal and 4% by weight surfactant;

FIG. 5 is a graph showing the switching response time data for the diffracted beam in the surfactant-containing PDLC material in FIG. 4;

FIG. 6 is a graph of the normalized net transmittance and the normalized net diffraction efficiency of a hologram;

FIG. 7 is an elevational view of typical experimental arrangement for recording reflection gratings;

FIGS. 8a and 8b are elevational views of a reflection grating, made in accordance with the teachings of the description herein, having periodic planes of polymer channels and PDLC channels disposed parallel to the front surface in the absence of a field (FIG. 8a) and with an electric field applied (FIG. 8b) wherein the liquid-crystal utilized in the formation of the grating has a positive dielectric anisotropy;

FIGS. 9a and 9b are elevational views of a reflection grating, made in accordance with the teachings of the description herein, having periodic planes of polymer channels and PDLC channels disposed parallel to the front surface of the grating in the absence of an electric field (FIG. 9a) and with an electric field applied (FIG. 9b) wherein the liquid crystal utilized in the formation of the grating has a negative dielectric anisotropy;

FIG. 10a is an elevational view of a reflection grating, made in accordance with the teachings of the description herein, disposed within a magnetic field generated by Helmholtz coils;

FIGS. 10b and 10c are elevational views of the reflection grating of FIG. 10a in the absence of an electric field (FIG. 10b) and with an electric field applied (FIG. 10c);

FIGS. 11a and 11b are representative side views of a slanted transmission grating (FIG. 11a) and a slanted reflection grating (FIG. 11b) showing the orientation of the grating vector  $G$  of the periodic planes of polymer channels and PDLC channels;

FIG. 12 is an elevational view of a reflection grating, made in accordance with the teachings of the description herein, when a shear stress field is applied thereto;

FIG. 13 is an elevational view of a subwavelength grating, made in accordance with the teachings of the description herein, having periodic planes of polymer channels and PDLC channels disposed perpendicular to the front surface of the grating;

FIG. 14a is an elevational view of a switchable subwavelength, made in accordance with the teachings of the description herein, wherein the subwavelength grating functions as a half wave plate whereby the polarization of the incident radiation is rotated by  $90^\circ$ ;

FIG. 14b is an elevational view of the switchable half wave plate shown in FIG. 14a disposed between crossed polarizers whereby the incident light is transmitted;

FIGS. 14c and 14d are side views of the switchable half wave plate and crossed polarizers shown in FIG. 14b and showing the effect of the application of a voltage to the plate whereby the polarization of the light is no longer rotated and thus blocked by the second polarizer;

FIG. 15a is a side view of a switchable subwavelength grating, made in accordance with the teachings of the description herein, wherein the subwavelength grating functions as a quarter wave plate whereby plane polarized light is transmitted through the subwavelength grating, retroreflected by a mirror and reflected by the beam splitter;

FIG. 15b is a side view of the switchable subwavelength grating of FIG. 15a and showing the effect of the application of a voltage to the plate whereby the polarization of the light is no longer modified, thereby permitting the reflected light to pass through the beam splitter;

FIGS. 16a and 16b are elevational views of a transmission grating, made in accordance with the teachings of the description herein, having periodic planes of polymer channels and PDLC channels disposed perpendicular to the front face of the grating in the absence of an electric field (FIG. 16a) and with an electric field applied (FIG. 16b) wherein the liquid crystal utilized in formation of the grating has a positive dielectric anisotropy;

FIG. 17 is a side view of five subwavelength gratings wherein the gratings are stacked and connected electrically in parallel thereby reducing the switching voltage of the subwavelength grating;

FIG. 18 is a schematic diagram of a bright light suppression system according to a first embodiment;

FIG. 19 is a schematic diagram of a portion of the bright light suppression system shown in FIG. 18 in which the overlap of the fields of views and regards is illustrated;

FIG. 20 is a schematic diagram of a bright light suppression system according to a second embodiment; and

FIG. 21 is a flow diagram of a method for a processing circuit to control a bright light suppression system.

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and will herein be described in detail. It should be understood, however, that the drawing and detailed description thereto are not intended to limit the invention to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

## **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

### **1. Switchable Hologram Materials And Devices**

The present invention employs holographic optical elements formed, in one embodiment, from a polymer dispersed liquid crystal (PDLC) material comprising a monomer, a dispersed liquid crystal, a cross-linking monomer, a co-initiator and a photo-initiator dye. These PDLC materials exhibit clear and orderly separation of the liquid crystal and cured polymer, whereby the PDLC material advantageously provides high quality optical elements. The PDLC materials used in the holographic optical elements may be formed in a single step. The holographic optical elements may also use a unique photopolymerizable prepolymer material that permits *in situ* control over characteristics of resulting gratings, such as domain size, shape, density, ordering and the like. Furthermore, methods and materials taught herein can be used to prepare PDLC materials for optical elements comprising switchable transmission or reflection type holographic gratings.

Polymer dispersed liquid crystal materials, methods, and devices contemplated for use in the present invention are also described in R. L. Sutherland et al., "Bragg Gratings in an Acrylate Polymer Consisting of Periodic Polymer dispersed Liquid-Crystal Planes," *Chemistry of Materials*, No. 5, pp. 1533-1538 (1993); in R. L. Sutherland et al., "Electrically switchable volume gratings in polymer dispersed liquid crystals," *Applied Physics Letters*, Vol. 64, No. 9, pp. 1074-1076 (1994); and T.J. Bunning et al., "The Morphology and Performance of Holographic Transmission Gratings Recorded in Polymer dispersed Liquid Crystals," *Polymer*, Vol. 36, No. 14, pp. 2699-2708 (1995), all of which are fully incorporated by reference into this Detailed

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Description. U.S. Patent application Serial Nos. 08/273, 436 and U.S. Patent 5,698,343 to Sutherland et al., titled "Switchable Volume Hologram Materials and Devices," and "Laser Wavelength Detection and Energy Dosimetry Badge," respectively, are also incorporated by reference and include background material on the formation of transmission gratings inside volume holograms.

5           The process by which a hologram for use in one embodiment of the present invention, may be formed is controlled primarily by the choice of components used to prepare the homogeneous starting mixture, and to a lesser extent by the intensity of the incident light pattern. In one embodiment of polymer dispersed liquid crystal (PDLC) material employed in the present invention creates a switchable hologram in a single step. A feature of one embodiment of PDLC material is that illumination by an inhomogeneous, coherent light pattern  
10 initiates a patterned, anisotropic diffusion (or counter diffusion) of polymerizable monomer and second phase material, particularly liquid crystal (LC). Thus, alternating well-defined channels of second phase-rich material, separated by well-defined channels of a nearly pure polymer, can be produced in a single-stop process.

          The resulting embodiment of PDLC material may have an anisotropic spatial distribution of phase-separated LC droplets within the photochemically cured polymer matrix. Prior art PDLC materials made by a  
15 single-step process can achieve at best only regions of larger LC bubbles and smaller LC bubbles in a polymer matrix. The large bubble sizes are highly scattering which produces a hazy appearance and multiple ordering diffractions, in contrast to the well-defined first order diffraction and zero order diffraction made possible by the small LC bubbles of one embodiment of PDLC material in well-defined channels of LC-rich material. Reasonably well-defined alternately LC-rich channels, and nearly pure polymer channels in a PDLC material  
20 are possible by multistep processes, but such processes do not achieve the precise morphology control over LC droplet size and distribution of sizes and widths of the polymer and LC-rich channels made possible by one embodiment of PDLC material.

          The same may be prepared by coating the mixture between two indium-tin-oxide (ITO) coated glass slides separated by spacers of nominally 10-20  $\mu\text{m}$  thickness. The sample is placed in a conventional  
25 holographic recording setup. Gratings are typically recorded using the 488 nm line of an Argon ion laser with intensities of between about 0.1-100 mW/cm<sup>2</sup> and typical exposure times of 30-120 seconds. The angle between the two beams is varied to vary the spacing of the intensity peaks, and hence the resulting grating spacing of the hologram. Photopolymerization is induced by the optical intensity pattern. A more detailed discussion of exemplary recording apparatus can be found in R.L. Sutherland, et al., "Switchable holograms in  
30 new photopolymer-liquid crystal composite materials," Society of Photo-Optical Instrumentation Engineers (SPIE), Proceedings Reprint, Volume 2402, reprinted from Diffraction and Holographic Optics Technology II (1995), incorporated herein by reference.

          The features of the PDLC material are influenced by the components used in the preparation of the homogeneous starting mixture and, to a lesser extent, by the intensity of the incident light pattern. In one  
35 embodiment, the prepolymer material comprises a mixture of a photopolymerizable monomer, a second phase material, a photo-initiator dye, a co-initiator, a chain extender (or cross-linker), and, optionally, a surfactant.

          In one embodiment, two major components of the prepolymer mixture are the polymerizable monomer and the second phase material, which are preferably completely miscible. Highly functionalized monomers may be preferred because they form densely cross-linked networks which shrink to some extent and to end to

squeeze out the second phase material. As a result, the second phase material is moved anisotropically out of the polymer region and, thereby, separated into well-defined polymer-poor, second phase-rich regions or domains. Highly functionalized monomers may also be preferred because the extensive cross-linking associated with such monomers yields fast kinetics, allowing the hologram to form relatively quickly, whereby the second phase material will exist in domains of less than approximately 0.1  $\mu\text{m}$ .

Highly functionalized monomers, however, are relatively viscous. As a result, these monomers do not tend to mix well with other materials, and they are difficult to spread into thin films. Accordingly, it is preferable to utilize a mixture of penta-acrylates in combination with di-, tri-, and/or tetra-acrylates in order to optimize both the functionality and viscosity of the prepolymer material. Suitable acrylates, such as triethyleneglycol diacrylate, trimethylolpropane triacrylate, pentaerythritol triacrylate, pentaerythritol tetracrylate, pentaerythritol pentacrylate, and the like can be used in the present invention. In one embodiment, it has been found that an approximately 1:4 mixture of tri- to penta-acrylate facilitates homogeneous mixing while providing a favorable mixture for forming 10-20  $\mu\text{m}$  films on the optical plates.

The second phase material of choice for use in the practice of the present invention is a liquid crystal (LC). This also allows an electro-optical response for the resulting hologram. The concentration of LC employed should be large enough to allow a significant phase separation to occur in the cured sample, but not so large as to make the sample opaque or very hazy. Below about 20% by weight very little phase separation occurs and diffraction efficiencies are low. Above about 35% by weight, the sample becomes highly scattering, reducing both diffraction efficiency and transmission. Samples fabricated with approximately 25% by weight typically yield good diffraction efficiency and optical clarity. In prepolymer mixtures utilizing a surfactant, the concentration of LC may be increased to 35% by weight without loss in optical performance by adjusting the quantity of surfactant. Suitable liquid crystals contemplated for use in the practice of the present invention may include the mixture of cyanobiphenyls marketed as E7 by Merck, 4'-n-pentyl-4-cyanobiphenyl, 4'-n-heptyl-4-cyanobiphenyl, 4'-octaoxy-4-cyanobiphenyl, 4'-pentyl-4-cyanoterphenyl,  $\alpha$ -methoxybenzylidene-4'-butylaniline, and the like. Other second phase components are also possible.

The polymer dispersed liquid crystal material employed in the practice of the present invention may be formed from a prepolymer material that is a homogeneous mixture of a polymerizable monomer comprising dipentaerythritol hydroxypentacrylate (available, for example, from Polysciences, Inc., Warrington, Pennsylvania), approximately 10-40 wt% of the liquid crystal E7 (which is a mixture of cyanobiphenyls marketed as E7 by Merck and also available from BDH Chemicals, Ltd., London, England), the chain-extending monomer N-vinylpyrrolidinone ("NVP") (available from the Aldrich Chemical Company, Milwaukee, Wisconsin), co-initiator N-phenylglycine ("NPG") (also available from the Aldrich Chemical Company, Milwaukee, Wisconsin), and the photo-initiator dye rose bengal ester; (2,4,5,7-tetraiodo-3',4',5',6'-tetrachlorofluorescein-6-acetate ester) marketed as RBAX by Spectragraph, Ltd., Maumee, Ohio). Rose bengal is also available as rose bengal sodium salt (which must be esterified for solubility) from the Aldrich Chemical Company. This system has a very fast curing speed which results in the formation of small liquid crystal microdroplets.

The mixture of liquid crystal and prepolymer material are homogenized to a viscous solution by suitable means (e.g., ultrasonification) and spread between indium-tin-oxide (ITO) coated glass sides with



spacers of nominally 15-100  $\mu\text{m}$  thickness and, preferably, 10-20  $\mu\text{m}$  thickness. The ITO is electrically conductive and serves as an optically transparent electrode. Preparation, mixing and transfer of the prepolymer material onto the glass slides are preferably done in the dark, as the mixture is extremely sensitive to light.

The sensitivity of the prepolymer materials to light intensity is dependent on the photo-initiator dye and its concentration. A higher dye concentration leads to a higher sensitivity. In most cases, however, the solubility of the photo-initiator dye limits the concentration of the dye and, thus, the sensitivity of the prepolymer material. Nevertheless, it has been found that for more general applications, photoinitiator dye concentrations in the range of 0.2-0.4% by weight are sufficient to achieve desirable sensitivities and allow for a complete bleaching of the dye in the recording process, resulting in colorless final samples. Photo-initiator dyes that may be useful in generating PDLC materials are rose bengal ester (2,4,5,7-tetraiodo-3',4',5',6'-tetrachlorofluorescein-6-acetate ester); rose bengal sodium salt; eosin; eosin sodium salt; 4,5-diiodosuccinyl fluorescein; camphorquinone; methylene blue, and the like. These dyes allow a sensitivity to recording wavelengths across the visible spectrum from nominally 400 nm to 700 nm. Suitable near-infrared dyes, such as cationic cyanine dyes with trialkylborate anions having absorption from 600-900 nm as well as merocyanine dyes derived from spiropyran may also find utility in the present invention.

The co-initiator employed in the practice of the present invention controls the rate of curing in the free radical polymerization reaction of the prepolymer material. Optimum phase separation and, thus, optimum diffraction efficiency in the resulting PDLC material, are a function of curing rate. It has been found that favorable results can be achieved utilizing co-initiator in the range of 2-3% by weight. Suitable co-initiators include N-phenylglycine; triethyl amine; triethanolamine; N,N-dimethyl-2,6-diisopropyl aniline, and the like.

Other suitable dyes and dye co-initiator combinations that may be suitable for use in the present invention, particularly for visible light, include eosin and triethanolamine; camphorquinone and N-phenylglycine; fluorescein and triethanolamine; methylene blue and triethanolamine or N-phenylglycine; erythrosin B and triethanolamine; indolinocarbocyanine and triphenyl borate; iodobenzospiropyran and triethylamine, and the like.

The chain extender (or cross linker) employed in the practice of the present invention may help to increase the solubility of the components in the prepolymer material as well as increase the speed of polymerization. The chain extender is preferably a smaller vinyl monomer as compared with the pentaerylate, whereby it can react with the acrylate positions in the pentaerylate monomer, which are not easily accessible to neighboring pentaerylate monomers due to steric hindrance. Thus, reaction of the chain extender monomer with the polymer increases the propagation length of the growing polymer and results in high molecular weights. It has been found that chain extender in general applications in the range of 10-18% by weight maximizes the performance in terms of diffraction efficiency. In the one embodiment, it is expected that suitable chain extenders can be selected from the following: N-vinylpyrrolidinone; N-vinyl pyridine; acrylonitrile; N-vinyl carbazole, and the like.

It has been found that the addition of a surfactant material, namely, octanoic acid, in the prepolymer material lowers the switching voltage and also improves the diffraction efficiency. In particular, the switching voltage for PDLC materials containing a surfactant are significantly lower than those of a PDLC material made without the surfactant. While not wishing to be bound by any particular theory, it is believed that these results

may be attributed to the weakening of the anchoring forces between the polymer and the phase-separated LC droplets. SEM studies have shown that droplet sizes in PDLC materials including surfactants are reduced to the range of 30-50nm and the distribution is more homogeneous. Random scattering in such materials is reduced due to the dominance of smaller droplets, thereby increasing the diffraction efficiency. Thus, it is believed that the shape of the droplets becomes more spherical in the presence of surfactant, thereby contributing to the decrease in switching voltage.

For more general applications, it has been found that samples with as low as 5% by weight of surfactant exhibit a significant reduction in switching voltage. It has also been found that, when optimizing for low switching voltages, the concentration of surfactant may vary up to about 10% by weight (mostly dependent on LC concentration) after which there is a large decrease in diffraction efficiency, as well as an increase in switching voltage (possibly due to a reduction in total phase separation of LC). Suitable surfactants include octanoic acid; heptanoic acid; hexanoic acid; dodecanoic acid; decanoic acid, and the like.

In samples utilizing octanoic acid as the surfactant, it has been observed that the conductivity of the sample is high, presumably owing to the presence of the free carboxyl (COOH) group in the octanoic acid. As a result, the sample increases in temperature when a high frequency (~2 kHz) electrical field is applied for prolonged periods of time. Thus, it is desirable to reduce the high conductivity introduced by the surfactant, without sacrificing the high diffraction efficiency and the low switching voltages. It has been found that suitable electrically switchable gratings can be formed from a polymerizable monomer, vinyl neononanoate ("VN")  $C_8H_{17}CO_2CH=CH_2$ , commercially available from the Aldrich Chemical Co. in Milwaukee, Wisconsin. Favorable results have also been obtained where the chain extender N-vinylpyrrolidinone ("NVP") and the surfactant octanoic acid are replaced by 6.5% by weight VN. VN also acts as a chain extender due to the presence of the reactive acrylate monomer group. In these variations, high optical quality samples were obtained with about 70% diffraction efficiency, and an applied field of  $6V/\mu m$  could electrically switch the resulting gratings.

PDLC materials used in the present invention may also be formed using a liquid crystalline bifunctional acrylate as the monomer ("LC monomer"). The LC monomers have an advantage over conventional acrylate monomers due to their high compatibility with the low molecular weight nematic LC materials, thereby facilitating formation of high concentrations of low molecular weight LC and yielding a sample with high optical quality. The presence of higher concentrations of low molecular weight LCs in the PDLC material greatly lowers the switching voltages (e.g., to  $\sim 2V/\mu m$ ). Another advantage of using LC monomers is that it is possible to apply low AC or DC fields while recording holograms to pre-align the host LC monomers and low molecular weight LC so that a desired orientation and configuration of the nematic directors can be obtained in the LC droplets. The chemical formulate of several suitable LC monomers are as follows:

- $CH_2=CH-COO-(CH_2)_6O-C_6H_5-C_6H_5-COO-CH=CH_2$
- $CH_2=CH-(CH_2)_8-COO-C_6H_5-COO-(CH_2)_8-CH=CH_2$
- $H(CF_2)_{10}CH_2O-CH_2-C(=CH_2)-COO-(CH_2CH_2O)_3CH_2CH_2O-COO-CH_2C(=CH_2)-CH_2O(CF_2)_{10}H$

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Semifluorinated polymers are known to show weaker anchoring properties and also significantly reduced switching fields. Thus, it is believed that semifluorinated acrylate monomers which are bifunctional and liquid crystalline may find suitable application in the present invention.

Referring now to FIG. 1, there is shown a cross-sectional view of an electrically switchable hologram 10 made of an exposed polymer dispersed liquid crystal material made according to the teachings of this description. A layer 12 of the polymer dispersed liquid crystal material is sandwiched between a pair of indium-tin-oxide coated glass slides 14 and spacers 16. The interior of hologram 10 shows Bragg transmission gratings 18 formed when layer 12 was exposed to an interference pattern from two intersecting beams of coherent laser light. The exposure times and intensities can be varied depending on the diffraction efficiency and liquid crystal domain size desired. Varying the concentrations of photo-initiator, co-initiator and chain-extending (or cross-linking) agent can control liquid crystal domain size. The orientation of the nematic directors can be controlled while the gratings are being recorded by application of an external electric field across the ITO electrodes.

The scanning electron micrograph shown in FIG. 2 of the referenced *Applied Physics Letters* article, and incorporated herein by reference, is of the surface of a grating which was recorded in a sample with a 36 wt% loading of liquid crystal using the 488 nm line of an argon ion laser at an intensity of 95 mW/cm<sup>2</sup>. The size of the liquid crystal domains is about 0.2  $\mu$ m and the grating spacing is about 0.54  $\mu$ m. This sample, which is approximately 20  $\mu$ m thick, diffracts light in the Bragg regime.

FIG. 2 is a graph of the normalized net transmittance and normalized net diffraction efficiency of a hologram made according to the teachings of his disclosure versus the root mean square voltage ("Vrms") applied across the hologram.  $\Delta\eta$  is the change in first order Bragg diffraction efficiency.  $\Delta T$  is the change in zero order transmittance. FIG. 2 shows that energy is transferred from the first order beam to the zero-order beam as the voltage is increased. There is a true minimum of the diffraction efficiency at approximately 225 Vrms. The peak diffraction efficiency can approach 100%, depending on the wavelength and polarization of the probe beam, by appropriate adjustment of the sample thickness. The minimum diffraction efficiency can be made to approach 0% by slight adjustment of the parameters of the PDLC material to force the refractive index of the cured polymer to be equal to the ordinary refractive index of the liquid crystal.

By increasing the frequency of the applied voltage, the switching voltage for minimum diffraction efficiency can be decreased significantly. This is illustrated in FIG. 3, which is a graph of both the threshold rms voltage 20 and the complete switching rms voltage 22 needed for switching a hologram made according to the teachings of this disclosure to minimum diffraction efficiency versus the frequency of the rms voltage. The threshold and complete switching rms voltages are reduced to 20 Vrms and 60 Vrms, respectively, at 10 kHz. Lower values are expected at even higher frequencies.

Smaller liquid crystal droplet sizes have the problem that it takes high switching voltages to switch their orientation. As described in the previous paragraph, using alternating current switching voltages at high frequencies helps reduce the needed switching voltage. As demonstrated in FIG. 4, it has been found that adding a surfactant (e.g., octanoic acid) the prepolymer material in amounts of about 4%-6% by weight of the total mixture results in sample holograms with switching voltages near 50Vrms at lower frequencies of 1-2 kHz. As shown in FIG. 5, it has also been found that the use of the surfactant with the associated reduction in droplet

size reduces the switching time of the PDLC materials. Thus, samples made with surfactant can be switched on the order of 25-44 microseconds. Without wishing to be bound by any theory, the surfactant is believed to reduce switching voltages by reducing the anchoring of the liquid crystals at the interface between liquid crystal and cured polymer.

5 Thermal control of diffraction efficiency is illustrated in FIG. 6. FIG. 6 is a graph of the normalized net transmittance and normalized net diffraction efficiency of a hologram made according to the teachings of this disclosure versus temperature.

The polymer dispersed liquid crystal materials described herein successfully demonstrate the utility for recording volume holograms of a particular composition for such polymer dispersed liquid crystal systems.

10 As shown in FIG. 7, a PDLC reflection grating is prepared by placing several drops of the mixture of prepolymer material 112 on an indium-tin oxide coated glass slide 114a. A second indium-tin oxide coated slide 114b is then pressed against the first, thereby causing the prepolymer material 112 to fill the region between the slides 114a and 114b. Preferably, the separation of the slides is maintained at approximately 20  $\mu\text{m}$  by utilizing uniform spacers 118. Preparation, mixing and transfer of the prepolymer material is preferably  
15 done in the dark. Once assembled, a mirror 116 may be placed directly behind the glass plate 114b. The distance of the mirror from the sample is preferably substantially shorter than the coherence length of the laser. The PDLC material is preferably exposed to the 488 nm line of an argon-ion laser, expanded to fill the entire plane of the glass plate, with an intensity of approximately 0.1-100 mWatts/cm<sup>2</sup> with typical exposure times of 30-120 seconds. Constructive and destructive interference within the expanded beam establishes a periodic  
20 intensity profile through the thickness of the film.

In one embodiment, the prepolymer material utilized to make a reflection grating comprises a monomer, a liquid crystal, a cross-linking monomer, a co-initiator, and a photo-initiator dye. The reflection grating may be formed from prepolymer material comprising by total weight of the monomer dipentaerythritol hydroxypentacrylate (DPHA), 35% by total weight of a liquid crystal comprising a mixture of cyano biphenyls  
25 (known commercially as "E7"), 10% by total weight of a cross-linking monomer comprising N-vinylpyrrolidinone ("NVP"), 2.5% by weight of the co-initiator N-phenylglycine ("NPG"), and  $10^{-5}$  to  $10^{-6}$  gram moles of a photo-initiator dye comprising rose bengal ester. Further, as with transmission gratings, the addition of surfactants is expected to facilitate the same advantageous properties discussed above in connection with transmission gratings. It is also expected that similar ranges and variation of prepolymer starting material will  
30 find ready application in the formation of suitable reflection gratings.

It has been determined by low voltage, high resolution scanning electron microscopy ("LVHRSEM") that the resulting material comprises a fine grating with a periodicity of 165 nm with the grating vector perpendicular to the plane of the surface. Thus, as shown schematically in FIG. 8a, grating 130 includes periodic planes of polymer channels 130a and PDLC channels 130b which run parallel to the front surface 134.  
35 The grating spacing associated with these periodic planes remains relatively constant throughout the full thickness of the sample from the air/film to the film/substrate interface.

Although interference is used to prepare both transmission and reflection gratings, the morphology of the reflection grating differs significantly. In particular, it has been determined that, unlike transmission gratings with similar liquid crystal concentrations, very little coalescence of individual droplets was evident. Further

more, the droplets that were present in the material were significantly smaller having diameters between 50 and 100 nm. Furthermore, unlike transmission gratings where the liquid crystal-rich regions typically comprise less than 40% of the grating, the liquid crystal-rich component of a reflection grating is significantly larger. Due to the much smaller periodicity associated with reflection gratings, i.e., a narrower grating spacing (~0.2 microns), it is believed that the time difference between completion of curing in high intensity versus low intensity regions is much smaller. It is also believed that the fast polymerization, as evidenced by small droplet diameters, traps a significant percentage of the liquid crystal in the matrix during gelation and precludes any substantial growth of large droplets or diffusion of small droplets into larger domains.

Analysis of the reflection notch in the absorbance spectrum supports the conclusion that a periodic refractive index modulation is disposed through the thickness of the film. In PDLC materials that are formed with the 488 nm line of an argon ion laser, the reflection notch typically has a reflection wavelength at approximately 472 nm for normal incidence and a relatively narrow bandwidth. The small difference between the writing wavelength and the reflection wavelength (approximately 5%) indicates that shrinkage of the film is not a significant problem. Moreover, it has been found that the performance of such gratings is stable over periods of many months.

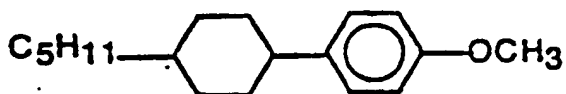
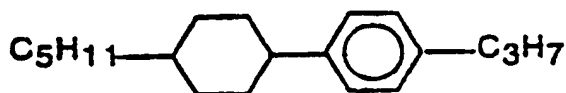
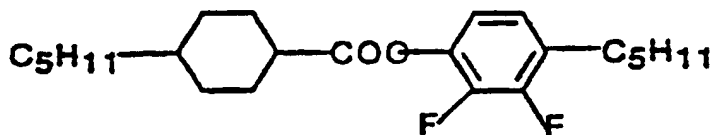
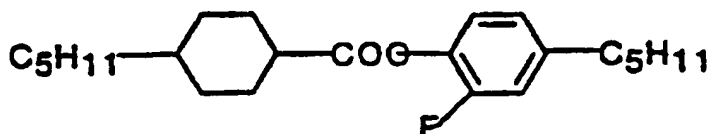
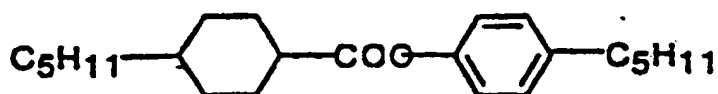
In addition to the materials utilized in the one embodiment described above, it is believed that suitable PDLC materials could be prepared utilizing monomers such as triethyleneglycol diacrylate, trimethylolpropanetriacrylate, pentaerythritol triacrylate, pentaerythritol tetracrylate, pentaerythritol pentacrylate, and the like. Similarly, other co-initiators such as triethylamine, triethanolamine, N,N-dimethyl-2,6-diisopropylaniline, and the like could be used instead of N-phenylglycine. Where it is desirable to use the 458 nm, 476 nm, 488 nm or 514 nm lines of an Argon ion laser, that the photo-initiator dyes rose bengal sodium salt, eosin, eosin sodium salt, fluorescein sodium salt and the like will give favorable results. Where the 633 nm line is utilized, methylene blue will find ready application. Finally, it is believed that other liquid crystals such as 4'-pentyl-4-cyanobiphenyl or 4'-heptyl-4-cyanobiphenyl, can be utilized.

Referring again to FIG. 8a, there is shown an elevational view of a reflection grating 130 made in accordance with this disclosure having periodic planes of polymer channels 130a and PDLC channels 130b disposed parallel to the front surface 134 of the grating 130. The symmetry axis 136 of the liquid crystal domains is formed in a direction perpendicular to the periodic channels 130a and 130b of the grating 130 and perpendicular to the front surface 134 of the grating 130. Thus, when an electric field E is applied, as shown in FIG. 8b, the symmetry axis 136 is already in a low energy state in alignment with the field E and will reorient. Thus, reflection gratings formed in accordance with the procedure described above will not normally be switchable.

In general, a reflection grating tends to reflect a narrow wavelength band, such that the grating can be used as a reflection filter. In one embodiment, however, the reflection grating is formed so that it will be switchable. More particularly, switchable reflection gratings can be made utilizing negative dielectric anisotropy LCs (or LCs with a low cross-over frequency), an applied magnetic field, an applied shear stress field, or slanted gratings.

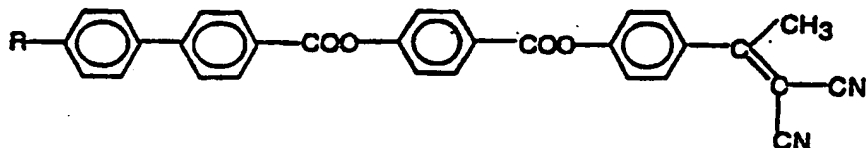
It is known that liquid crystals having a negative dielectric anisotropy ( $\Delta\epsilon$ ) will rotate in a direction perpendicular to an applied field. As shown in FIG. 9a, the symmetry axis 136 of the liquid crystal domains

formed with a liquid crystal having a negative  $\Delta\epsilon$  will also be disposed in a direction perpendicular to the periodic channels 130a and 130b of the grating 130 and to the front surface 135 of the grating. However, when an electric field E is applied across such gratings, as shown in FIG. 9b, the symmetry axis of the negative  $\Delta\epsilon$  liquid crystal will distort and reorient in a direction perpendicular to the field E, which is perpendicular to the film and the periodic planes of the grating. As a result, the reflection grating can be switched between a state where it is reflective and a state where it is transmissive. The following negative  $\Delta\epsilon$  liquid crystals and others are expected to find ready applications in the methods and devices of the present invention:

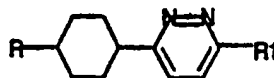


Liquid crystals can be found in nature (or synthesized) with either positive or negative  $\Delta\epsilon$ . Thus, it is possible to use a LC which has a positive  $\Delta\epsilon$  at low frequencies, but becomes negative at high frequencies. The frequency (of the applied voltage) at which  $\Delta\epsilon$  changes sign is called the crossover frequency. The cross-over frequency will vary with LC composition, and typical values range from 1-10 kHz. Thus, by operating at the proper frequency, the reflection grating may be switched. It is expected that low crossover frequency materials can be prepared from a combination of positive and negative dielectric anisotropy liquid

crystals. A suitable positive dielectric liquid crystal for use in such a combination contains four ring esters as shown below:



5 A strongly negative dielectric liquid crystal suitable for use in such a combination is made up of pyridazines as shown below:



Both liquid crystal materials are available from LaRoche & Co., Switzerland. By varying the proportion of the positive and negative liquid crystals in the combination, crossover frequencies from 1.4-2.3 kHz are obtained at room temperature. Another combination suitable for use in the present embodiment is a combination of the following: p-pentylphenyl-2-chloro-4-(p-pentylbenzoyloxy) benzoate and benzoate. These materials are available from Kodak Company.

In still more detailed aspects, switchable reflection gratings can be formed using positive  $\Delta\epsilon$  liquid crystals. As shown in FIG. 10a, such gratings are formed by exposing the PDLC starting material to a magnetic field during the curing process. The magnetic field can be generated by the use of Helmholtz coils (as shown in FIG. 10a), the use of a permanent magnet, or other suitable means. Preferably, the magnetic field M is oriented parallel to the front surface of the glass plates (not shown) that are used to form the grating 140. As a result, the symmetry axis 146 of the liquid crystals will orient along the field while the mixture is fluid. When polymerization is complete, the field may be removed and the alignment of the symmetry axis of the liquid crystals will remain unchanged. (See FIG. 10b.) When an electric field is applied, as shown in FIG. 10c the positive  $\Delta\epsilon$  liquid crystal will reorient in the direction of the field, which is perpendicular to the front surface of grating and to the periodic channels of the grating.

FIG. 11a depicts a slanted transmission grating 148 and FIG. 11b depicts a slanted reflection grating 150. A holographic transmission grating is considered slanted if the direction of the grating vector G is not parallel to the grating surface. In a holographic reflection grating, the grating is said to be slanted if the grating

vector  $G$  is not perpendicular to the grating surface. Slanted gratings have many of the same uses as non-slanted grating such as visual displays, mirrors, line filters, optical switches, and the like.

Primarily, slanted holographic gratings are used to control the direction of a diffracted beam. For example, in reflection holograms a slanted grating is used to separate the specular reflection of the film from the diffracted beam. In a PDLC holographic grating, a slanted grating has an even more useful advantage. The slant allows the modulation depth of the grating to be controlled by an electric field when using either tangential or homeotropic aligned liquid crystals. This is because the slant provides components of the electric field in the directions both tangent and perpendicular to the grating vector. In particular, for the reflection grating, the LC domain symmetry axis will be oriented along the grating vector  $G$  and can be switched to a direction perpendicular to the film plane by a longitudinally applied field  $E$ . This is the typical geometry for switching of the diffraction efficiency of the slanted reflection grating.

When recording slanted reflection gratings, it is desirable to place the sample between the hypotenuses of two right-angle glass prisms. Neutral density filters can then be placed in optical contact with the back faces of the prisms using index matching fluids so as to frustrate back reflections which would cause spurious gratings to also be recorded. A conventional beam splitter splits the incident laser beam into two beams which are directed to the front faces of the prisms, and then overlapped in the sample at the desired angle. The beams thus enter the sample from opposite sides. This prism coupling technique permits the light to enter the sample at greater angles. The slant of the resulting grating is determined by the angle which the prism assembly is rotated (i.e., the angle between the direction of one incident beam and the normal to the prism front face at which that beam enters the prism).

As shown in FIG. 12, switchable reflection gratings may be formed in the presence of an applied shear stress field. In this method, a shear stress would be applied along the direction of a magnetic field  $M$ . This could be accomplished, for example, by applying equal and opposite tensions to the two ITO coated glass plates which sandwich the prepolymer mixture while the polymer is still soft. This shear stress would distort the LC domains in the direction of the stress, and the resultant LC domain symmetry axis will be preferentially along the direction of the stress, parallel to the PDLC planes and perpendicular to the direction of the applied electric field for switching.

Reflection grating prepared in accordance with this description may find application in color reflective displays, switchable wavelength filters for laser protection, reflective optical elements and the like.

In one embodiment, PDLC materials can be made that exhibit a property known as form birefringence whereby polarized light that is transmitted through the grating will have its polarization modified. Such gratings are known as subwavelength gratings, and they behave like a negative uniaxial crystal, such as calcite, potassium dihydrogen phosphate, or lithium niobate, with an optic axis perpendicular to the PDLC planes. Referring now to FIG. 13, there is shown an elevational view of a transmission grating 200 made in accordance with this description having periodic planes of polymer planes 200a and PDLC planes 200b disposed perpendicular to the front surface 204 of the grating 200. The optic axis 206 is disposed perpendicular to polymer planes 200a and the PDLC planes 200b. Each polymer plane 200a has a thickness  $t_p$  and refractive index  $n_p$ , and each PDLC plane 200b has a thickness  $t_{PDL}$  and refractive index  $n_{PDL}$ .



Where the combined thickness of the PDLC plane and the polymer plane is substantially less than an optical wavelength (i.e.  $(t_{\text{PDL}} + t_p) \ll \lambda$ ), the grating will exhibit form birefringence. As discussed below, the magnitude of the shift in polarization is proportional to the length of the grating. Thus, by carefully selecting the length,  $L$ , of the subwavelength grating for a given wavelength of light, one can rotate the plane of polarization or create circularly polarized light. Consequently, such subwavelength gratings can be designed to act as a half-wave or quarter-wave plate, respectively. Thus, an advantage of this process is that the birefringence of the material may be controlled by simple design parameters and optimized to a particular wavelength, rather than relying on the given birefringence of any material at that wavelength.

To form a half-wave plate, the retardance of the subwavelength grating must be equal to one-half of a wavelength, i.e., retardance =  $\lambda/2$ , and to form a quarter-wave plate, the retardance must be equal to one-quarter of a wavelength, i.e., retardance =  $\lambda/4$ . It is known that the retardance is related to the net birefringence,  $|\Delta n|$ , which is the difference between the ordinary index of refraction,  $n_o$ , and the extraordinary index of refraction  $n_e$ , of the sub-wavelength grating by the following relation:

$$\text{Retardance} = |\Delta n| L = |n_e - n_o| L$$

Thus, for a half-wave plate, i.e. a retardation equal to one-half of a wavelength, the length of the subwavelength grating should be selected so that:

$$L = \lambda / (2 |\Delta n|)$$

Similarly, for a quarter-wave plate, i.e., a retardance equal to one-quarter of a wavelength, the length of the subwavelength grating should be selected so that:

$$L = \lambda / (4 |\Delta n|)$$

If, for example, the polarization of the incident light is at an angle of  $45^\circ$  with respect to the optic axis of a half-wave plate 212, as shown in FIG. 14a, the plane polarization will be preserved, but the polarization of the wave exiting the plate will be shifted by  $90^\circ$ . Thus, referring now to FIG. 14b and 14c, where the half-wave plate 212 is placed between cross-polarizers 214 and 216, the incident light will be transmitted. If an appropriate switching voltage is applied, as shown in FIG. 14d, the polarization of the light is not rotated and the second polarizer will block the light.

For a quarter-wave plate plane polarized light is converted to circularly polarized light. Thus, referring now to FIG. 15a, where quarter-wave plate 217 is placed between a polarizing beam splitter 218 and a mirror 219, the reflected light will be reflected by the beam splitter 218. If an appropriate switching voltage is applied, as shown in FIG. 15b, the reflected light will pass through the beam splitter and be retroreflected on the incident beam.

Referring now to FIG. 16a, there is shown an elevational view of a subwavelength grating 230 recorded in accordance with the above-described methods and having periodic planes of polymer channels 230a and PDLC channels 230b disposed perpendicular to the front surface 234 of grating 230. As shown in FIG. 16a, the symmetry axis 232 of the liquid crystal domains is disposed in a direction parallel to the front surface 234 of the grating and perpendicular to the periodic channels 230a and 230b of the grating 230. Thus, when an electric field E is applied across the grating, as shown in FIG. 15b, the symmetry axis 232 distorts and reorients in a direction along the field E, which is perpendicular to the front surface 234 of the grating, and parallel to the periodic channels 230a and 230b of the grating 230. As a result, subwavelength grating 230 can be switched between a state where it changes the polarization of the incident radiation and a state in which it does not. Without wishing to be bound by any theory, it is currently believed that the direction of the liquid crystal domain symmetry 232 is due to a surface tension gradient which occurs as a result of the anisotropic diffusion of monomer and liquid crystal during recording of the grating, and that this gradient causes the liquid crystal domain symmetry to orient in a direction perpendicular to the periodic planes.

As discussed in Born and Wolf, Principles of Optics, 5<sup>th</sup> Ed., New York (1975) and incorporated herein by reference, the birefringence of a subwavelength grating is given by the following relation:

$$n_e^2 - n_o^2 = -[(f_{\text{PDLC}})(f_p)(n_{\text{PDLC}}^2 - n_p^2)] / [f_{\text{PDLC}} n_{\text{PDLC}}^2 + f_p n_p^2]$$

Where

- $n_o$  = the ordinary index of refraction of the subwavelength grating;
- $n_e$  = the extraordinary index of refraction;
- $n_{\text{PDLC}}$  = the refractive index of the PDLC plane;
- $n_p$  = the refractive index of the polymer plane
- $n_{\text{LC}}$  = the effective refractive index of the liquid crystal seen by an incident optical wave;
- $f_{\text{PDLC}}$  =  $t_{\text{PDLC}} / (t_{\text{PDLC}} + t_p)$
- $f_p$  =  $t_p / (t_{\text{PDLC}} + t_p)$

Thus, the net birefringence of the subwavelength grating will be zero if  $n_{\text{PDLC}} = n_p$ .

It is known that the effective refractive index of the liquid crystal,  $n_{\text{LC}}$ , is a function of the applied electric field, having a maximum when the field is zero and value equal to that of the polymer,  $n_p$ , at some value of the electric field,  $E_{\text{MAX}}$ . Thus, by application of an electric field, the refractive index of the liquid crystal,  $n_{\text{LC}}$ , and, hence, the refractive index of the PDLC plane can be altered. Using the relationship set forth above, the net birefringence of a subwavelength grating will be a minimum when  $n_{\text{PDLC}}$  is equal to  $n_p$ , i.e. when  $n_{\text{LC}} = n_p$ . Therefore, if the refractive index of the PDLC plane can be matched to the refractive index of the polymer plane, i.e.  $n_{\text{PDLC}} = n_p$ , by the application of an electric field, the birefringence of the subwavelength grating can be switched off.

The following equation for net birefringence, i.e.  $|\Delta n| = |n_e - n_o|$ , follows from the equation given in Born and Wolf (reproduced above):

$$\Delta n = -[(f_{\text{PDL}})(f_p)(n_{\text{PDL}}^2 - n_p^2)] / [2n_{\text{AVG}}(f_{\text{PDL}} n_{\text{PDL}}^2 + f_p n_p^2)]$$

$$\text{where } n_{\text{AVG}} = (n_e + n_o) / 2$$

Furthermore, it is known that the refractive index of the PDL plane  $n_{\text{PDL}}$  is related to the effective refractive index of the liquid crystal seen by an incident optical wave,  $n_{\text{LC}}$ , and the refractive index of the surrounding polymer plane,  $n_p$ , by the following relation:

$$n_{\text{PDL}} = n_p + f_{\text{LC}} [n_{\text{LC}} - n_p]$$

Where  $f_{\text{LC}}$  is the volume fraction of liquid crystal dispersed in the polymer within the PDL plane,  $f_{\text{LC}} = [V_{\text{LC}} / (V_{\text{LC}} + V_p)]$ .

By way of example, a typical value for the effective refractive index for the liquid crystal in the absence of an electric field is  $n_{\text{LC}} = 1.7$ , and for the polymer layer  $n_p = 1.5$ . For the grating where the thickness of the PDL planes and the polymer planes are equal (i.e.  $t_{\text{PDL}} = t_p$ ,  $f_{\text{PDL}} = 0.5 = f_p$ ) and  $f_{\text{LC}} = 0.35$ , the net birefringence,  $\Delta n$ , of the subwavelength grating is approximately 0.008. Thus, where the incident light has a wavelength of  $0.8 \mu\text{m}$ , the length of the subwavelength grating should be  $50 \mu\text{m}$  for a half-wave plate and a  $25 \mu\text{m}$  for a quarter-wave plate. Furthermore, by application of an electric field of approximately  $5 \text{ V}/\mu\text{m}$ , the refractive index of the liquid crystal can be matched to the refractive index of the polymer and the birefringence of the subwavelength grating turned off. Thus, the switching voltage,  $V_n$ , for a half-wave plate is on the order of 250 volts, and for a quarter-wave plate approximately 125 volts.

By applying such voltages, the plates can be switched between the on and off (zero retardance) states on the order of microseconds. As a means of comparison, current Pockels cell technology can be switched in nanoseconds with voltages of approximately 1000-2000 volts, and bulk nematic liquid crystals can be switched on the order of milliseconds with voltages of approximately 5 volts.

In an alternative embodiment, as shown in FIG. 17, the switching voltage of the subwavelength grating can be reduced by stacking several subwavelength gratings 220a-220e together, and connecting them electrically in parallel. By way of example, it has been found that a stack of five gratings each with a length of  $10 \mu\text{m}$  yields the thickness required for a half-wave plate. It should be noted that the length of the sample is somewhat greater than  $50 \mu\text{m}$ , because each grating includes an indium-tin-oxide coating which acts as a transparent electrode. The switching voltage for such a stack of plates, however, is only 50 volts.

Subwavelength gratings in accordance with the this description are expected to find suitable application in the areas of polarization optics and optical switches for displays and laser optics, as well as tunable filters for telecommunications, colorimetry, spectroscopy, laser protection, and the like. Similarly,

electrically switchable transmission gratings have many applications for which beams of light must be deflected or holographic images switched. Among these applications are: Fiber optic switches, reprogrammable NxN optical interconnects for optical computing, beam steering for laser surgery, beam steering for laser radar, holographic image storage and retrieval, digital zoom optics (switchable holographic lenses), graphic arts and entertainment, and the like.

A switchable hologram is one for which the diffraction efficiency of the hologram may be modulated by the application of an electric field, and can be switched from a fully on state (high diffraction efficiency) to a fully off state (low or zero diffraction efficiency). A static hologram is one whose properties remain fixed independent of an applied field. In accordance with this description, a high contrast status hologram can also be created. In this variation of this description, the holograms are recorded as described previously. The cured polymer film is then soaked in a suitable solvent at room temperature for a short duration and finally dried. For the liquid crystal E7, methanol has shown satisfactory application. Other potential solvents include alcohols such as ethanol, hydrocarbons such as hexane and heptane, and the like. When the material is dried, a high contrast status hologram with high diffraction efficiency results. The high diffraction efficiency is a consequence of the large index modulation in the film ( $\Delta n \sim 0.5$ ) because the second phase domains are replaced with empty (air) voids ( $n \sim 1$ ).

Similarly, in accordance with this description a high birefringence static sub-wavelength wave-plate can also be formed. Due to the fact that the refractive index for air is significantly lower than for most liquid crystals, the corresponding thickness of the half-wave plate would be reduced accordingly. Synthesized wave-plates in accordance with this description can be used in many applications employing polarization optics, particularly where a material of the appropriate birefringence that the appropriate wavelength is unavailable, too costly, or too bulky.

The term polymer dispersed liquid crystals and polymer dispersed liquid crystal material includes, as may be appropriate, solutions in which none of the monomers have yet polymerized or cured, solutions in which some polymerization has occurred, and solutions which have undergone complete polymerization. Those skilled in the art will clearly understand that the use herein of the standard term used in the art, "polymer dispersed liquid crystals" (which grammatically refers to liquid crystals dispersed in a fully polymerized matrix) is meant to include all or part of a more grammatically correct prepolymer dispersed liquid crystal material, or a more grammatically correct starting material for a polymer dispersed liquid crystal material.

## 2. Bright Light Suppression Using Holographic Optical Elements

FIG. 18 shows a schematic diagram of a bright light suppression system according to a first embodiment. System 300 includes switchable holographic optical elements (SHOEs) 302, detectors 304, and processing circuit 306 coupled to SHOEs 302 and detectors 304. System 300 may be worn by a person as glasses or goggles. System 300 may also be incorporated in an optical device such as binoculars or gun sights. System 300 may further be incorporated into a device, such as a CCD or photomultiplier, that needs protection from bright lights.

SHOEs 302 may comprise any type of switchable holographic elements and preferably comprise switchable Bragg holograms fabricated using a polymer dispersed liquid crystal material due to their fast

switching rate, low switching voltage, and high diffraction efficiency. If SHOEs 302 comprise Bragg holograms, they may be either the transmission type (i.e., light is incident on a first surface and diffracted light exits a second surface) or the reflective type (i.e., light is incident on a first surface and diffracted light exits from the first surface). SHOEs 302 are preferably transmission-type Bragg holograms due to their large spectral bandwidth. The angular bandwidth of each SHOE 302 may be approximately 15° to 20° in air (i.e., the angular bandwidth corresponds to a cone with a half angle of approximately 7.5° to 10°). If system 300 is to be used to protect a person's eyes, the wavelength bandwidth of SHOEs 302 is preferably selected to give maximum diffraction efficiency around the human visual peak spectral response. If system 300 is used to protect a light-sensitive device, the wavelength bandwidth of SHOEs 302 is preferably selected to give maximum diffraction efficiency around the device's peak spectral response.

Detectors 304 may comprise any detector capable of outputting a signal indicative of the intensity of light incident on the detector. Examples of suitable detectors include photodiodes and phototransistors.

Each SHOE 302 has a corresponding field of view 308 while each detector 304 has a corresponding field of regard 310. Field of view 308 is determined by the angular bandwidth of SHOE 302 which is defined by the recording conditions of SHOE 302. Field of regard 310 for each detector 304 is determined by optical subsystem 312 which may comprise a set of lenses or apertures. Each SHOE 302 is paired with a detector 304 such that their corresponding fields of view and regard cover substantially the same points in space. For example, SHOE 302a has a field of view 308a while detector 304a has a field of regard 310a that covers substantially the same points in space for points sufficiently far from system 300. FIG. 19 shows field of view 308a and field of regard 310a and their volume of overlap 320. FIG. 19 illustrates that fields of 308a and 310a cover substantially the same points for points sufficiently far from system 300. For example, at a distance corresponding to light source 322, field of view 308a and field of regard 310a cover substantially the same points in space.

Although only four SHOEs 302 and four detectors 304 are shown in FIG. 18, system 300 may contain more than or less than this amount. There may be a sufficient number of SHOEs 302 and detectors 304 to cover a hemispherical viewing area. Adjacent field of views 308 may partially overlap or each field of view 308 may be unique. When SHOE 302 is deactivated, all light incident on SHOE 302 is transmitted substantially unaltered such that it may be seen by viewer 314. When SHOE 302 is activated, a portion of the light incident on SHOE 302 within the angular bandwidth of SHOE 302 is diffracted such that it may not be seen by viewer 314. Viewer 314 may be a person or a device such as a CCD. If SHOEs 302 are of the transmission type, optical stop 316 may be located between SHOEs 302 and viewer 314 to prevent any diffracted light from reaching viewer 314.

Processing circuit 306 monitors the output of detectors 304. The output of detectors 304 indicates whether or not a bright light is within field of regard 310 and, preferably, also indicates the quantity of intensity of the bright light. When no bright lights are detected, circuit 306 deactivates all of SHOEs 302. When a bright light is detected by one of detectors 304, circuit 306 activates the corresponding SHOE 302. If SHOEs 302 are polymer dispersed liquid crystal as described above in the preceding section, circuit 306 activates SHOE 302 by applying a first voltage and deactivates SHOE 302 by applying a second voltage.

By way of an example, if bright light source 322 is present within fields of view 308a and regard 310a (as shown in FIG. 19), detector 304a may output a signal to circuit 306 indicating an intensity of the light incident on detector 304a. Circuit 306 may then activate SHOE 302a by applying a first voltage to SHOE 302a. Circuit 306 may apply a magnitude of the first voltage such that SHOE 302a diffracts the maximum amount of light possible for SHOE 302a. Alternatively, circuit 306 may apply a magnitude of the first voltage such that SHOE 302a diffracts only a portion of the light incident on SHOE 302a. For example, if SHOE 302a is a Bragg hologram comprised of polymer dispersed liquid crystal material, the amount of light diffracted depends on the magnitude of the first voltage as shown in FIG. 2. In this way, the amount of light transmitted by SHOE 302a to viewer 314 may remain relatively constant.

Once bright light source 322 leaves fields of view 308a and regard 310a, detector 304a may output a signal to circuit 306 indicating the absence of a bright light source. Circuit 306 may then deactivate SHOE 302a by applying a second voltage to SHOE 302a.

FIG. 20 shows a schematic diagram of a bright light suppression system according to a second embodiment. Portions of system 330 shown in FIG. 20 similar to that of system 300 shown in FIG. 18 are labeled identically. System 330 includes SHOEs 302, detectors 304, and processing circuit 306. The principal difference between systems 300 and 330 is that system 300 stacks SHOEs 302 together while system 330 tiles SHOEs 330 next to one another. System 330 may further include optical subsystem 332 such that light transmitted by SHOEs 302 may be combined into a single image for viewer 314. Optical subsystem 332 may be comprised of a set of lenses. System 330 works in the same manner described above for system 300. Although detectors 304 are shown placed together off to the side of all SHOEs 302, detectors 304 may be placed differently. For instance, each detector 304 may be placed next to its corresponding SHOE 302.

FIG. 21 is a flow diagram of a method for a processing circuit to control a bright light suppression system. The flow diagram illustrates the method used by circuit 306 for either system 300 or system 330. Initially, circuit 306 checks the output of one of detectors 304 (box 340). Circuit 306 may monitor the output of all detectors 304 simultaneously or may check each of detectors 304 sequentially. Circuit 306 then determines if the brightness level of light incident by detector 304 exceeds a predetermined threshold value (box 342). If the level exceeds the threshold value, circuit 306 activates the SHOE 302 corresponding to detector 304 by applying a first voltage to SHOE 302 (box 344). A magnitude of the first voltage may be varied depending on a quantity of light incident on detector 304 to adjust the amount of light diffracted by SHOE 302. If the level does not exceed the threshold value, circuit 306 deactivates the SHOE 302 corresponding to detector 304 by applying a second voltage to SHOE 302 (box 346).

While the present invention has been described with reference to particular embodiments, it will be understood that the embodiments are illustrated and that the invention scope is not so limited. Any variations, modifications, additions and improvements to the embodiments described are possible. These variations, modifications, additions and improvements may fall within the scope of the invention as detailed within the following claims.

**WHAT IS CLAIMED IS:**

1. An apparatus, comprising:
  - 5 a switchable holographic optical element (SHOE), wherein the SHOE is configured to receive and diffract light originating from a point in space when activated, and wherein the SHOE is configured to receive and substantially transmit light, without substantial alteration, originating from the point in space when deactivated;
  - a detector configured to receive and detect light originating from the point in space; and
  - 10 a circuit coupled to the SHOE and the detector, wherein the circuit is configured to activate the SHOE in response to the detector receiving and detecting light originating from the point in space.
2. The apparatus of claim 1, wherein the SHOE diffracts a controllable portion of the received light when activated.
- 15 3. The apparatus of claim 2, wherein the circuit activates the SHOE by applying a first voltage to the SHOE, and wherein the portion of light diffracted depends on the first voltage.
4. The apparatus of claim 3, wherein a magnitude of the first voltage applied by the circuit depends on a quantity of light detected by the detector.
- 20 5. The apparatus of claim 1, wherein the SHOE is formed from polymer dispersed liquid crystal material.
6. The apparatus of claim 1, further comprising:
  - 25 a plurality of SHOEs, wherein each of the plurality of SHOEs is configured to receive and diffract light originating from a range of points in space when activated, and wherein each of the plurality of SHOEs is configured to receive and substantially transmit light, without substantial alteration, originating from the range of points in space when deactivated;
  - a plurality of detectors, wherein each of the plurality of detectors is configured to receive and detect light originating from the range of points in space corresponding to one of the plurality of SHOEs; and
  - 30 wherein the circuit is coupled to the plurality of SHOEs and the plurality of detectors, and wherein the circuit is configured to activate one of the plurality of SHOEs in response to the corresponding detector receiving and detecting light originating from the range of points in space.
- 35 7. The apparatus of claim 6, wherein the plurality of SHOEs are stacked together.
8. A method, comprising:
  - detecting light incident on a detector from a point in space; and

diffracting light incident on a SHOE from the point of space in response to said detecting.

9. The method of claim 8, wherein said diffracting comprises diffracting a controllable portion of the incident light.

5

10. The method of claim 9, further comprising activating the SHOE, subsequent to said detecting and prior to said diffracting.

11. The method of claim 10, wherein said activating comprises applying a first voltage to the SHOE, and  
10 wherein the portion of light diffracted depends on the first voltage.

12. The method of claim 11, wherein a magnitude of the first voltage depends on a quantity of the incident light detected.

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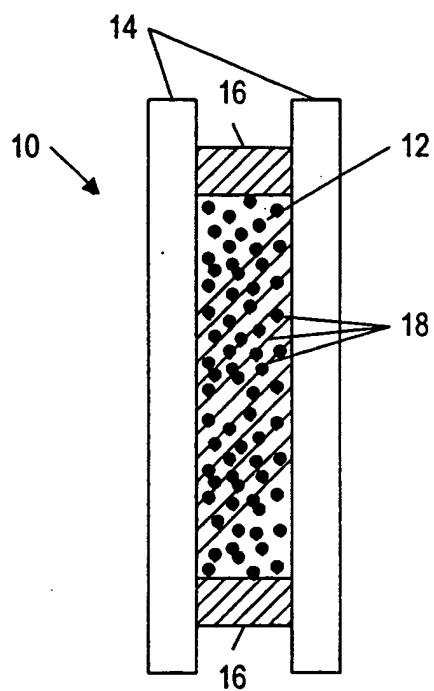


FIG. 1

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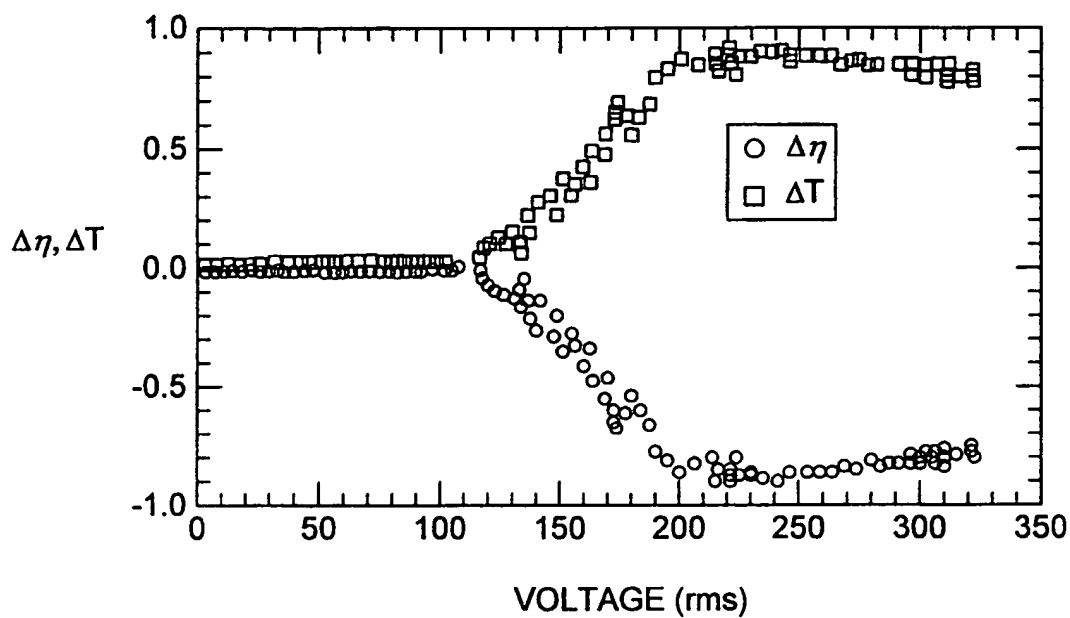


FIG. 2

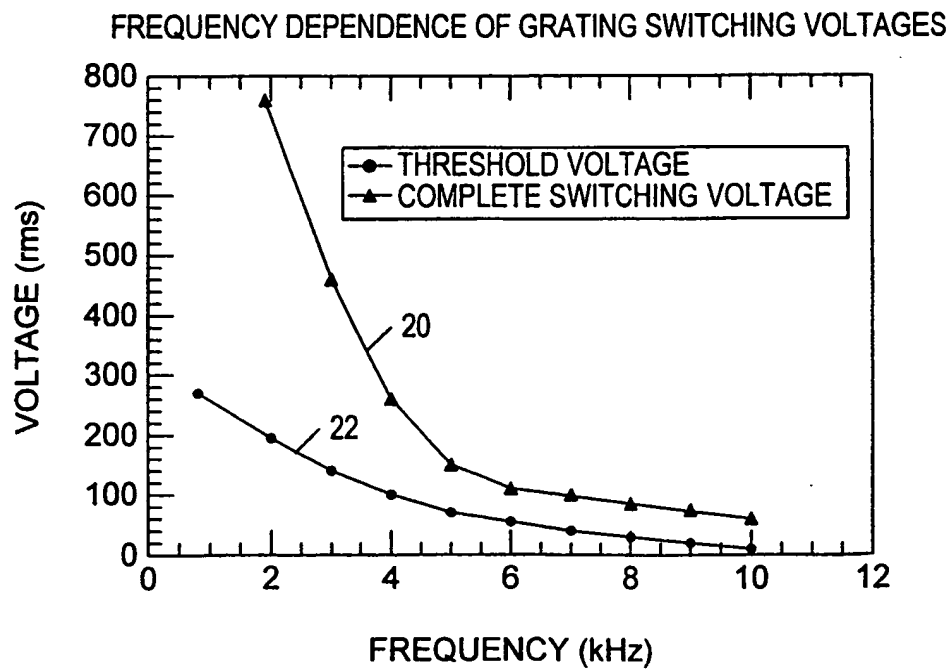


FIG. 3

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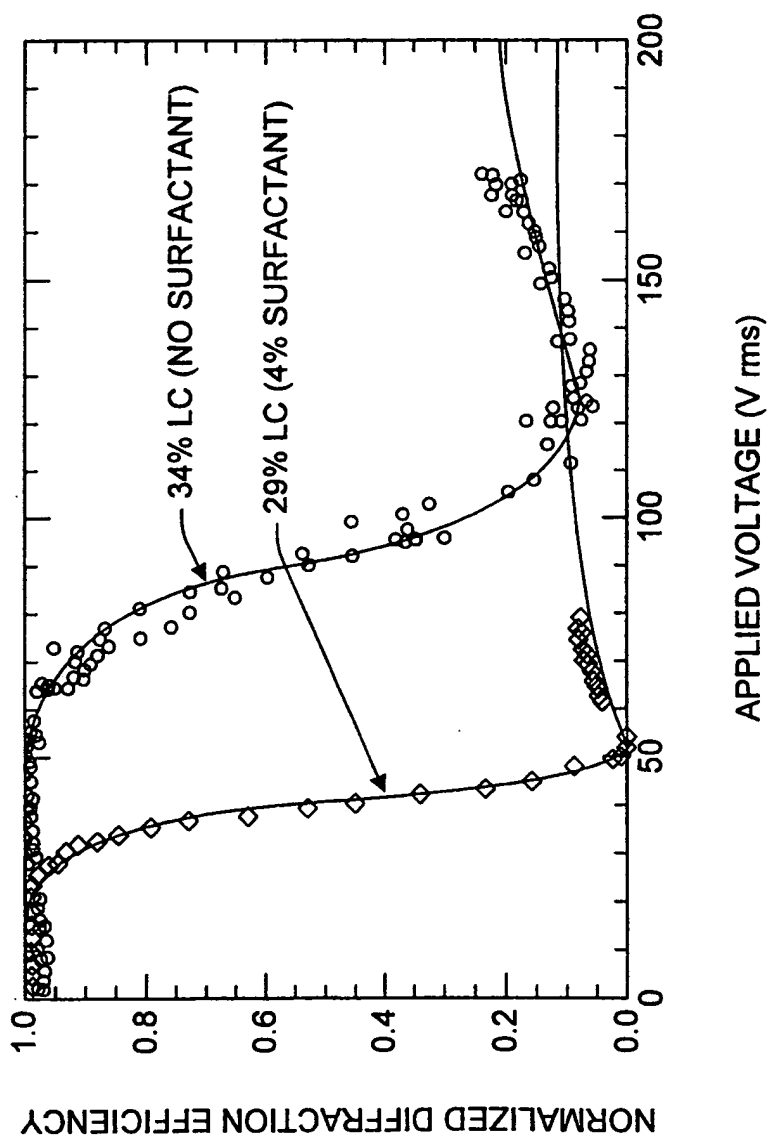


FIG. 4

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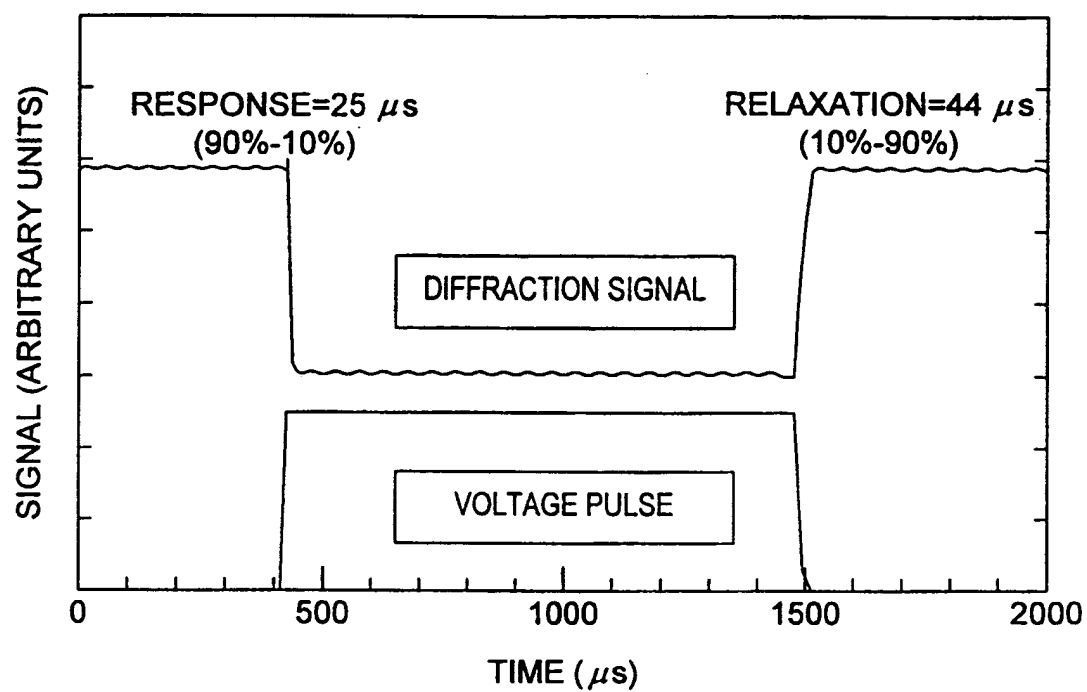


FIG. 5

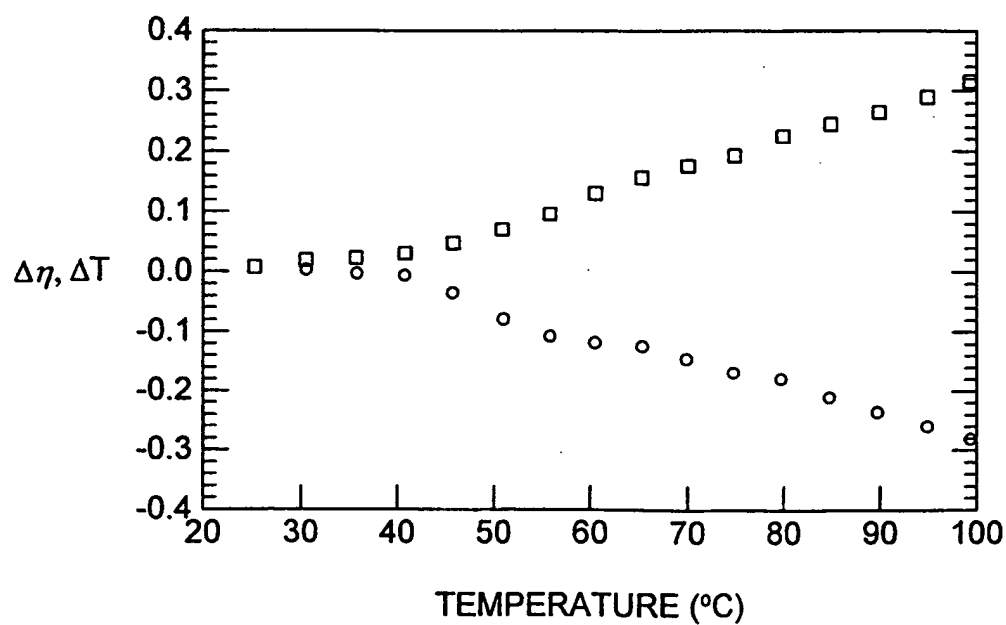


FIG. 6

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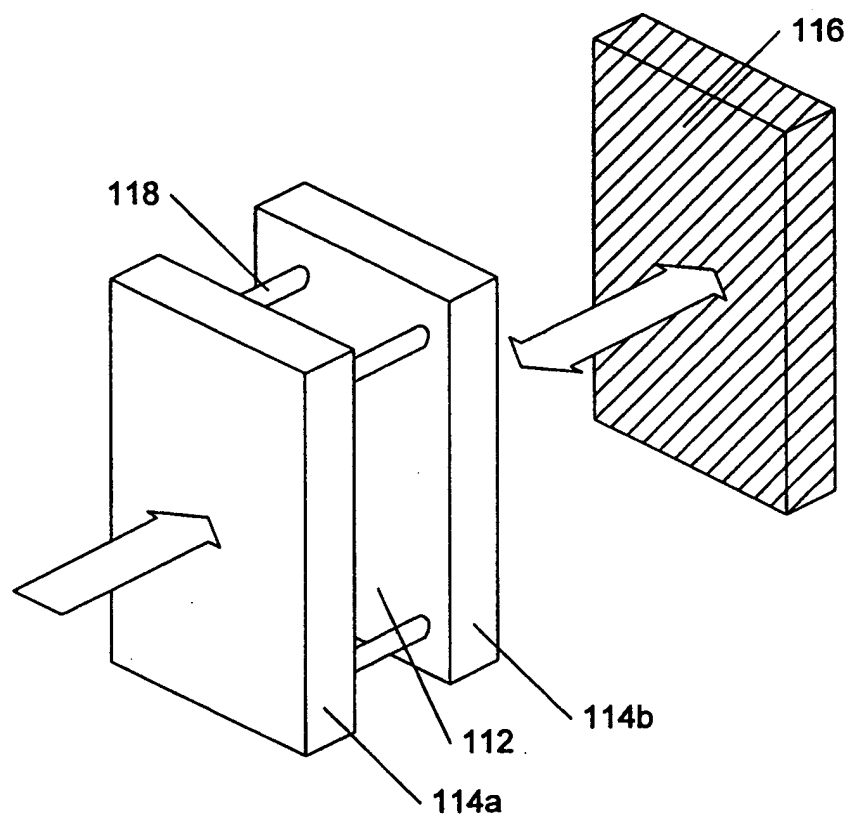


FIG. 7

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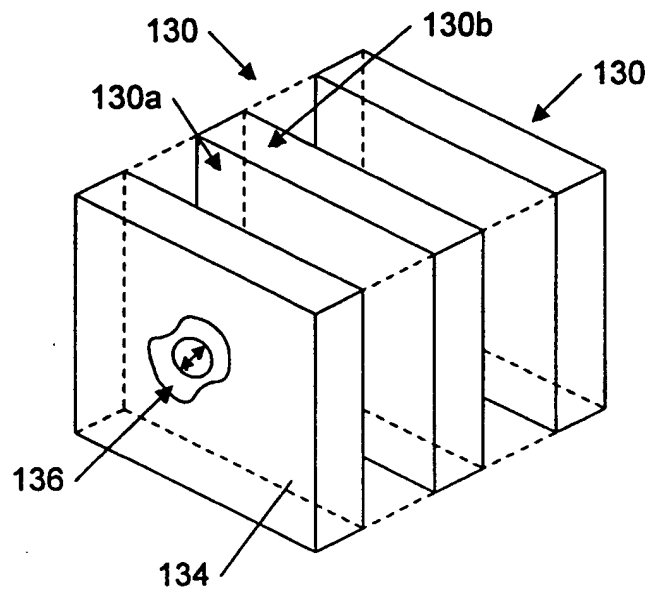


FIG. 8a

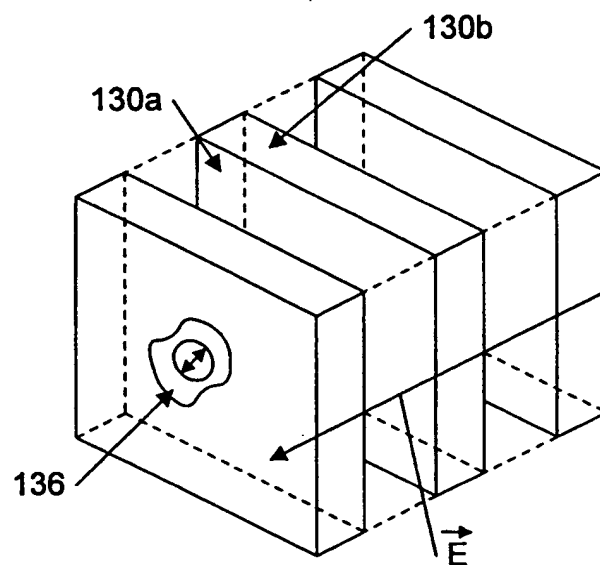


FIG. 8b

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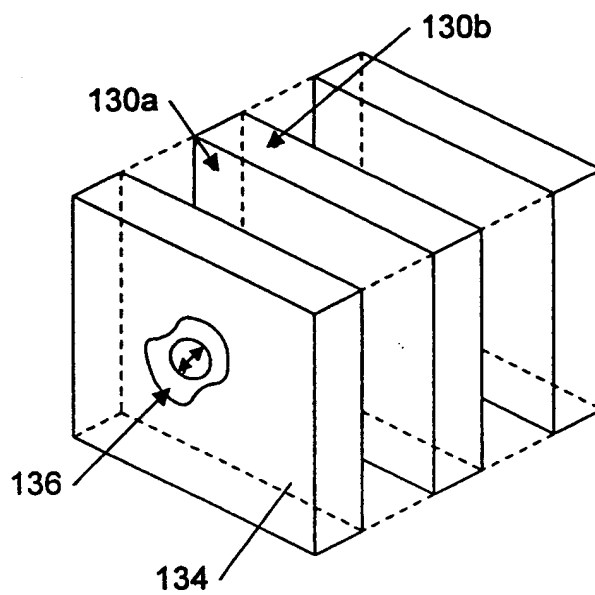


FIG. 9a

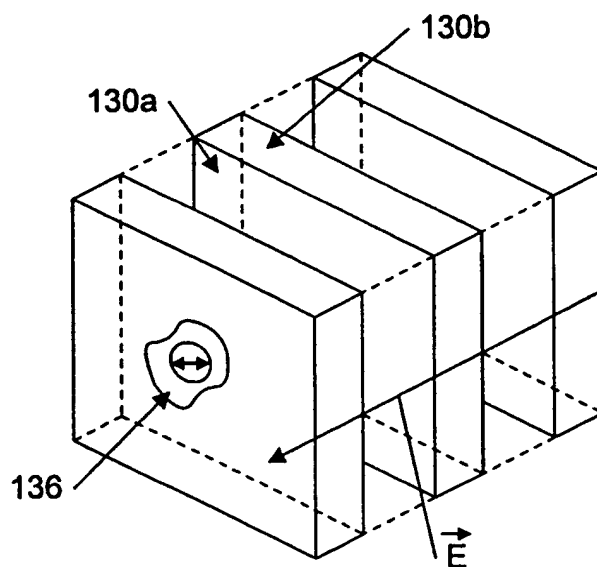


FIG. 9b

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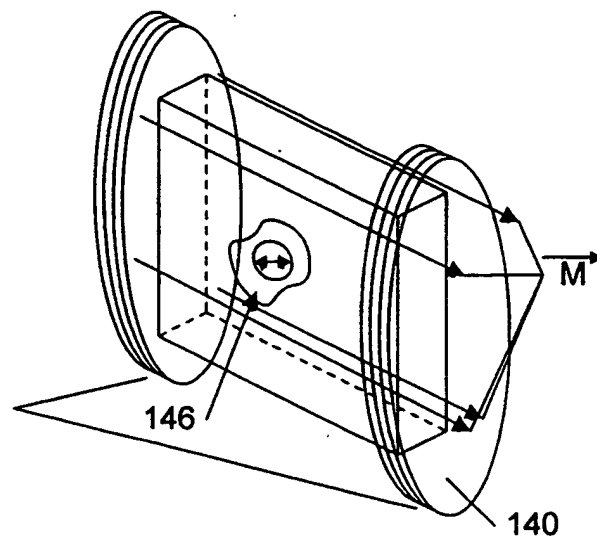


FIG. 10a

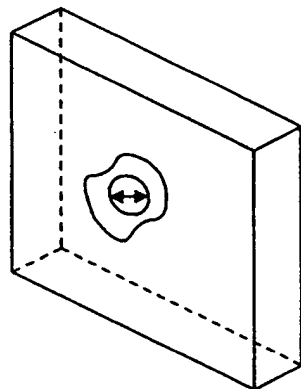


FIG. 10b

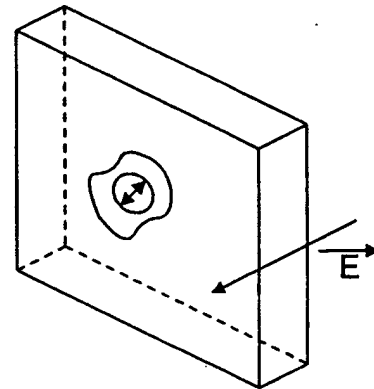


FIG. 10c



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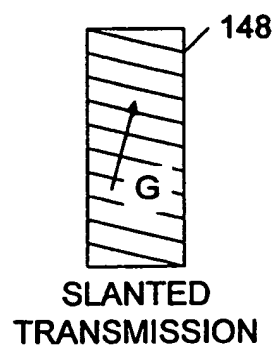


FIG. 11a

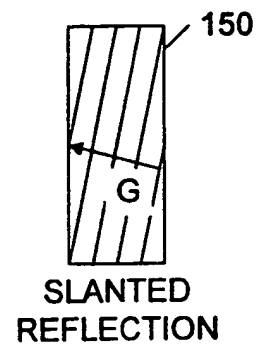


FIG. 11b

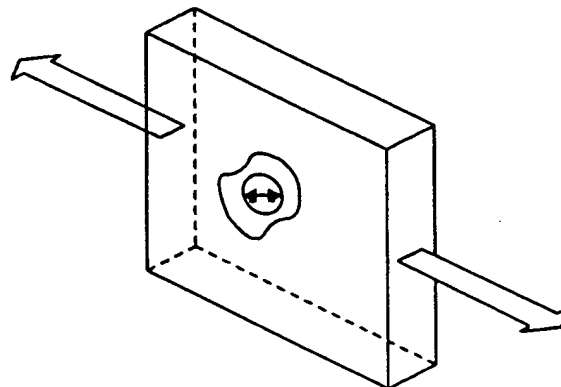


FIG. 12

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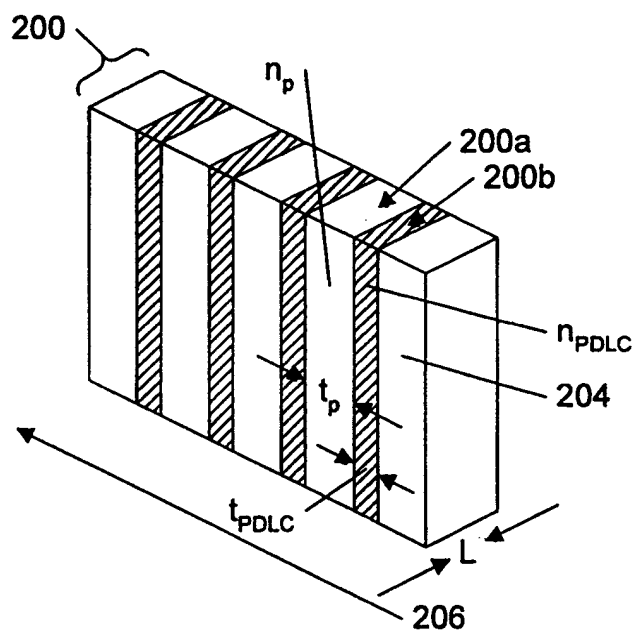


FIG. 13

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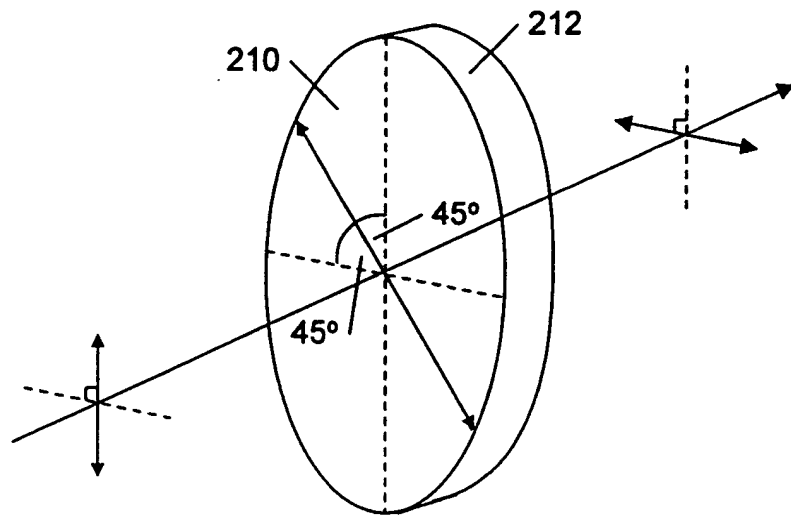


FIG. 14a

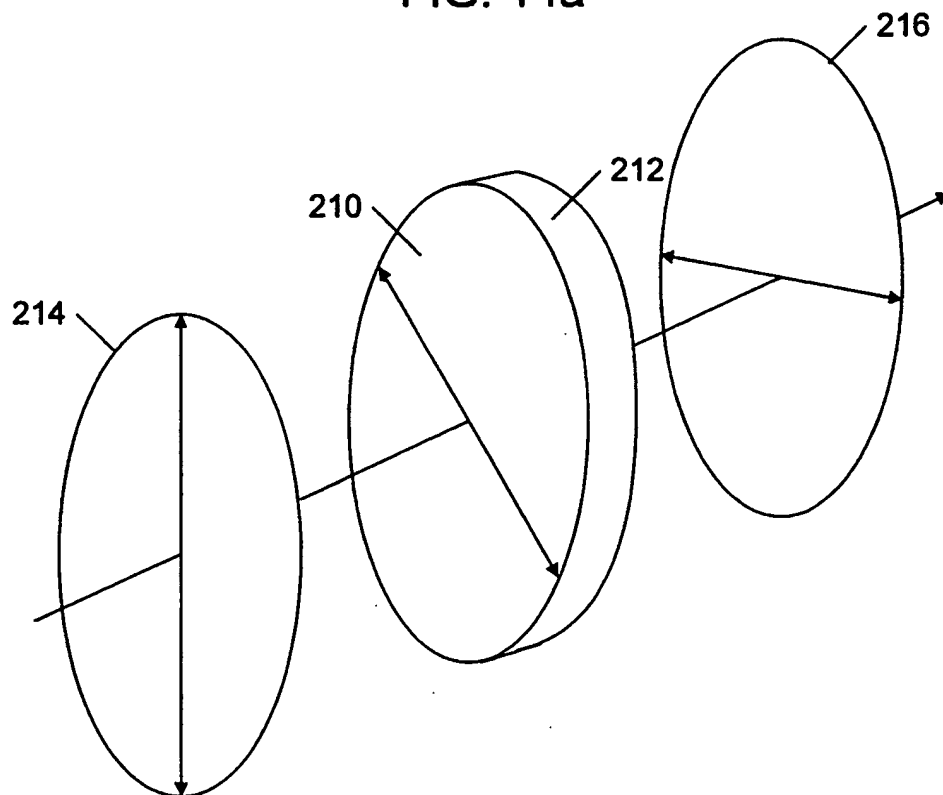
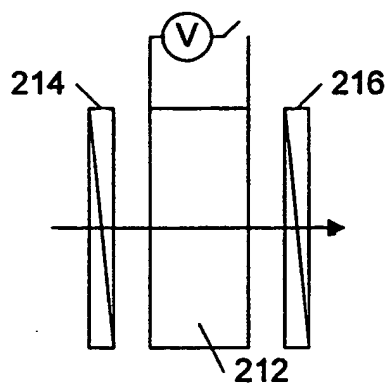


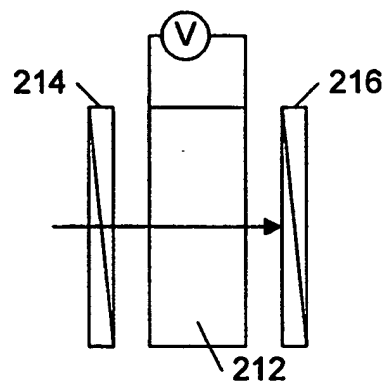
FIG. 14b

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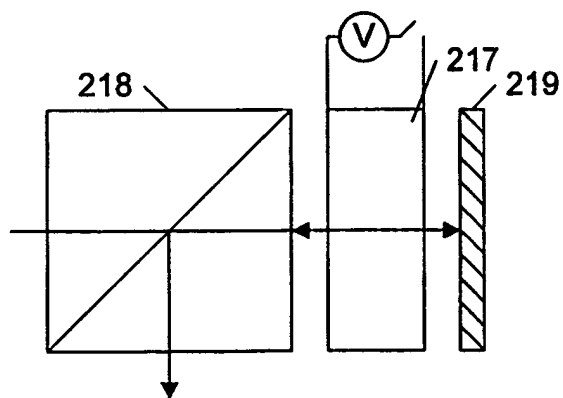
LIGHT TRANSMITTED

FIG. 14c



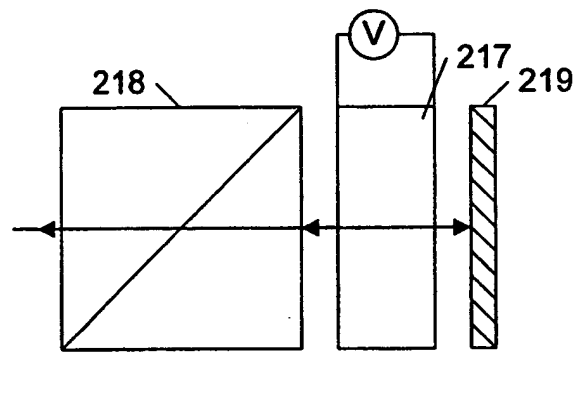
LIGHT BLOCKED

FIG. 14d



TRANSMITTED

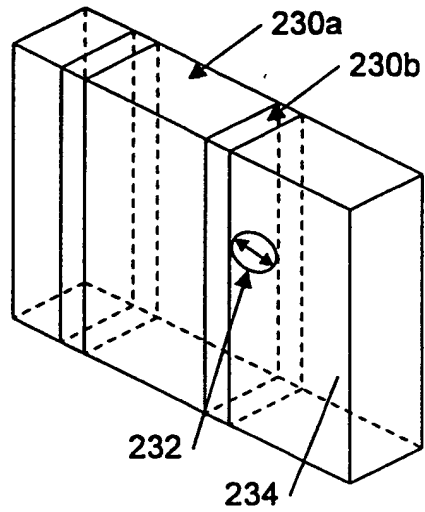
FIG. 15a



RETRO-REFLECTED

FIG. 15b

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UNSWITCHED STATE

FIG. 16a

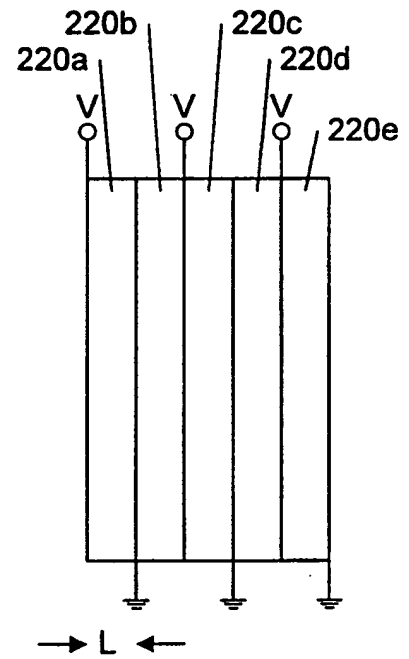
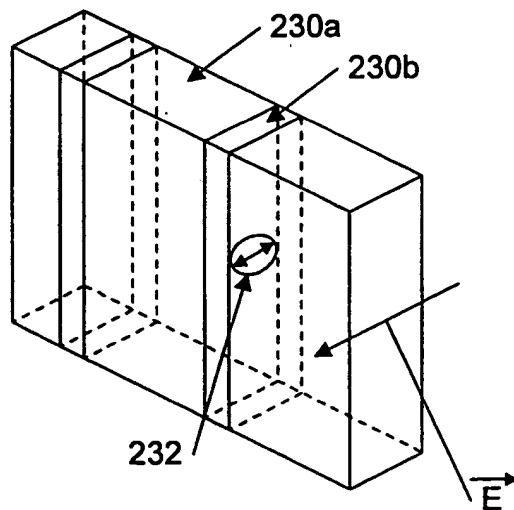


FIG. 17



SWITCHED STATE

FIG. 16b

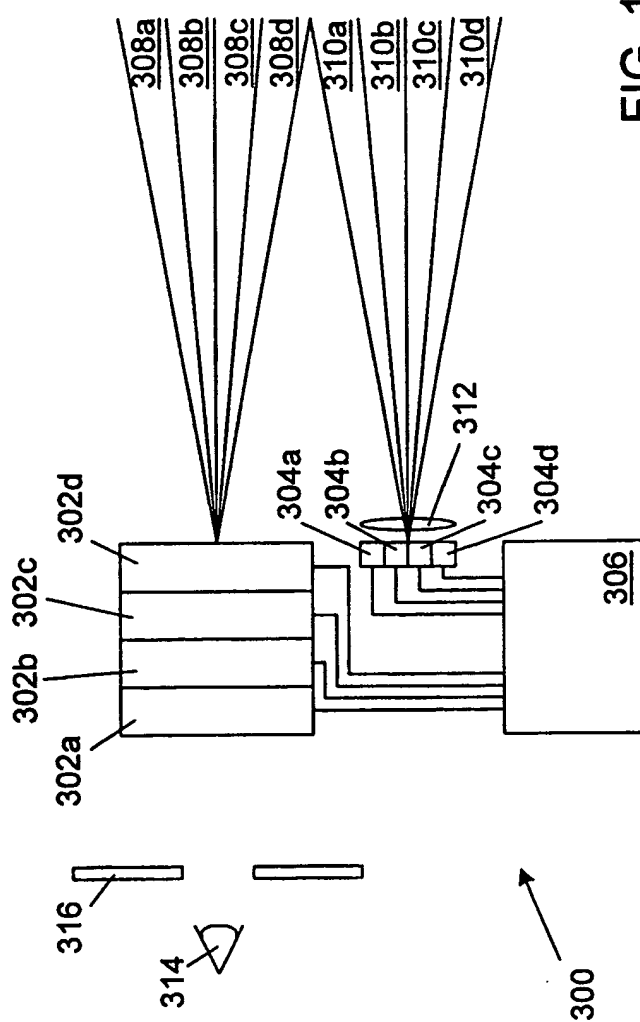


FIG. 18

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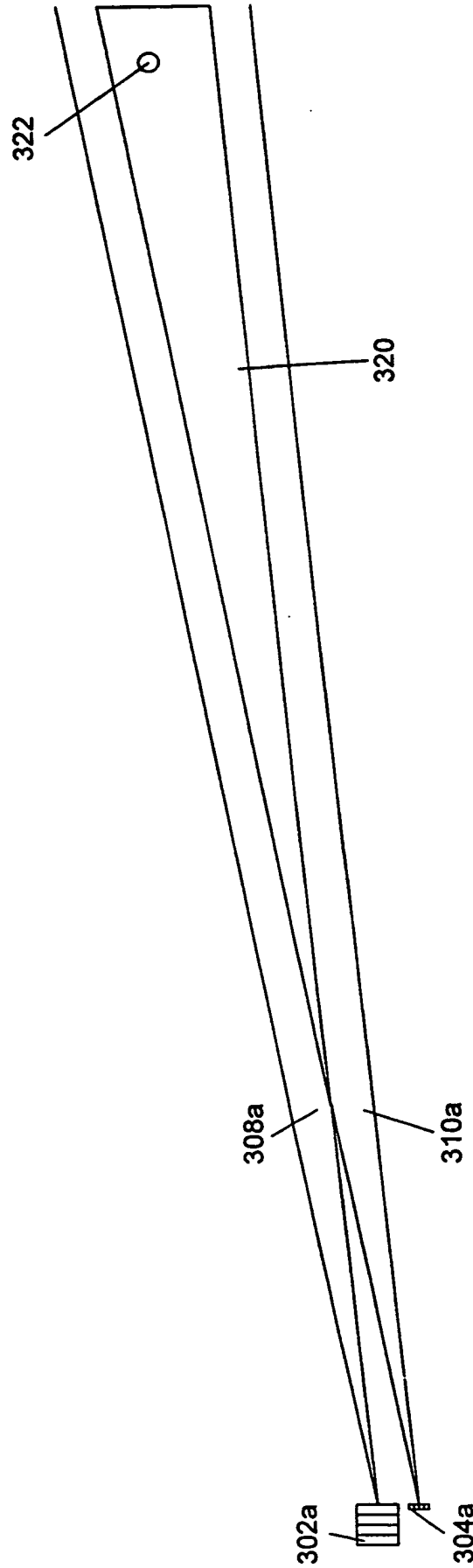


FIG. 19

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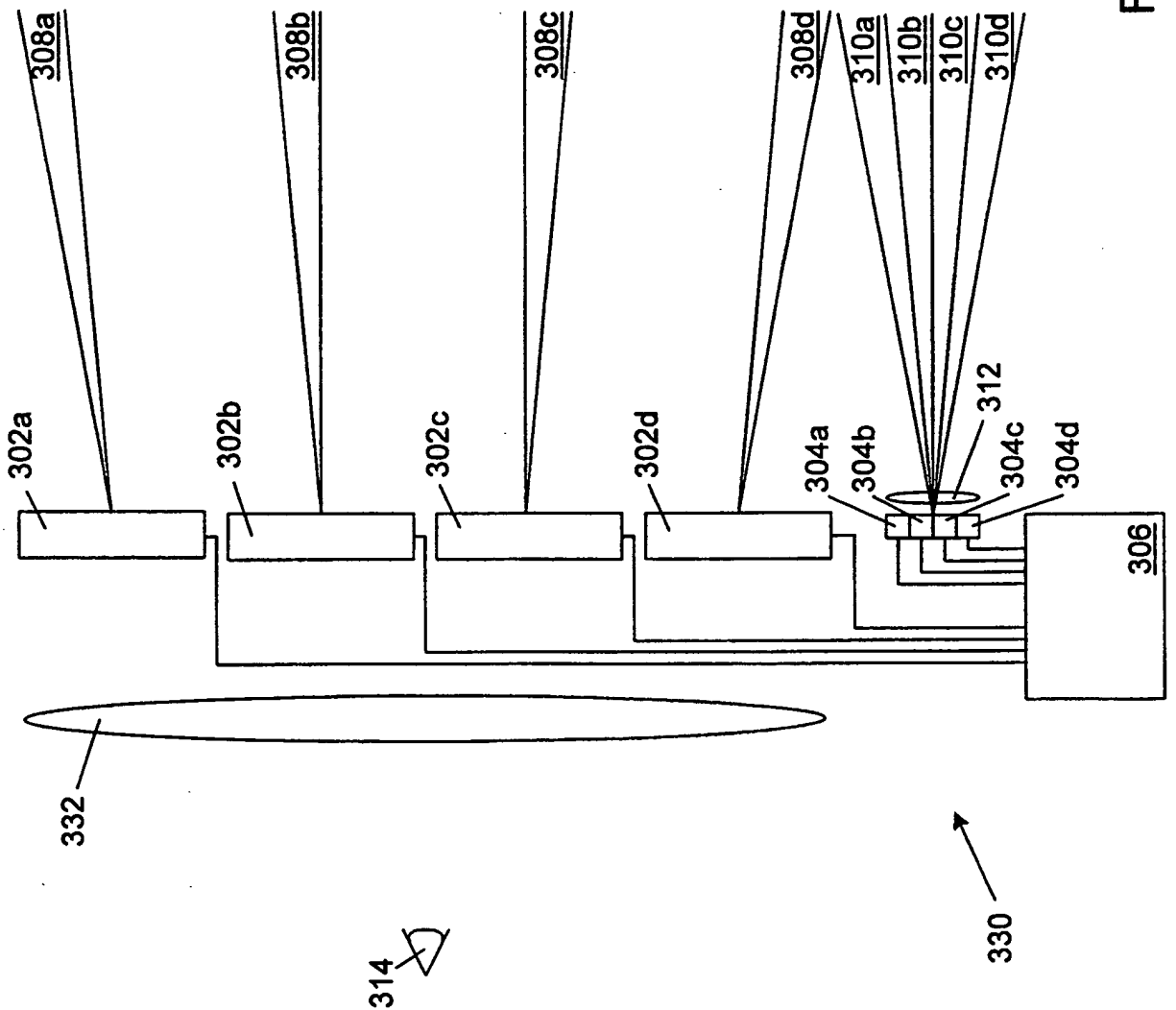


FIG. 20



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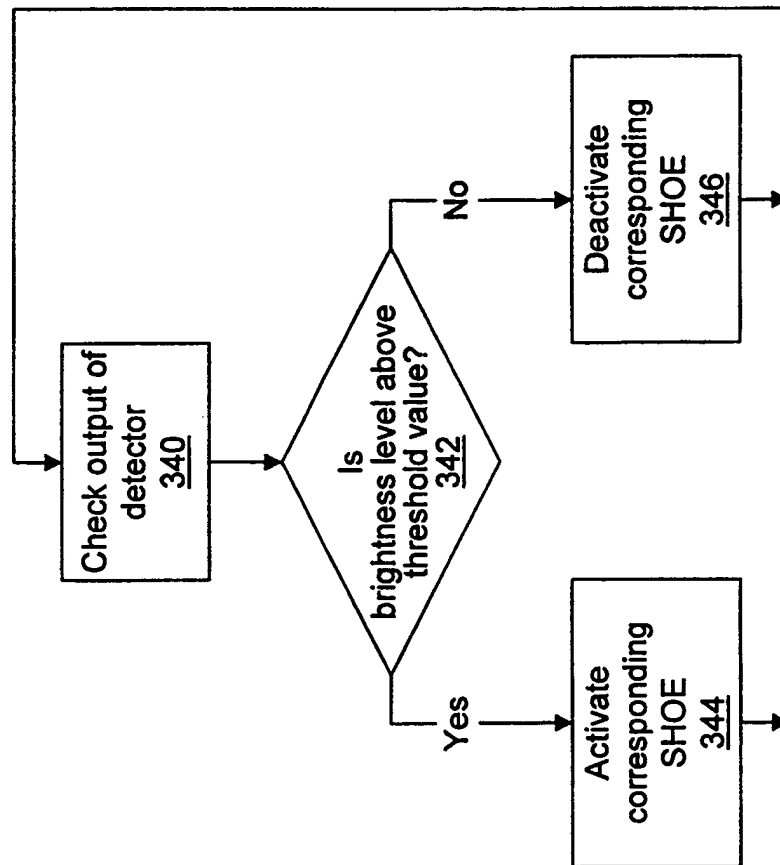


FIG. 21

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 99/24158

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 7 G02B5/32 G02B5/20

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)  
IPC 7 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 98 04650 A (SCIENCE APPLIC INT CORP) 5 February 1998 (1998-02-05) the whole document	1-5, 8-12
Y	SUTHERLAND R L: "OPTICAL LIMITERS, SWITCHES, AND FILTERS BASED ON POLYMER DISPERSED LIQUID CRYSTALS" PROCEEDINGS OF THE SPIE, vol. 1080, 31 December 1989 (1989-12-31), pages 83-90, XP000775987 page 84, paragraph 3.2 figure 2	1-5, 8-12



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

\* Special categories of cited documents:

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- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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- "&" document member of the same patent family

Date of the actual completion of the international search

25 January 2000

Date of mailing of the international search report

02/02/2000

Name and mailing address of the ISA

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Authorized officer

Mollenhauer, R

## INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 99/24158

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DOMASH L H ET AL: "APPLICATIONS OF SWITCHABLE POLAROID HOLOGRAMS" PROCEEDINGS OF THE SPIE,US,SPIE, BELLINGHAM, VA, vol. 2152, 26 January 1994 (1994-01-26), page 127-138 XP002057590 figure 1	6,7
A	BUNNING T J ET AL: "The morphology and performance of holographic transmission gratings recorded in polymer dispersed liquid crystals" POLYMER,GB,ELSEVIER SCIENCE PUBLISHERS B.V, vol. 36, no. 14, 31 December 1995 (1995-12-31), page 2699-2708 XP004025694 ISSN: 0032-3861 cited in the application figures 7,9	1-5
A	SUTHERLAND R L ET AL: "ELECTRICALLY SWITCHABLE VOLUME GRATINGS IN POLYMER-DISPERSED LIQUIDCRYSTALS" APPLIED PHYSICS LETTERS,US,AMERICAN INSTITUTE OF PHYSICS. NEW YORK, vol. 64, no. 9, 28 February 1994 (1994-02-28), page 1074-1076 XP000425907 ISSN: 0003-6951 cited in the application figure 2	1-5
A	SUTHERLAND R L ET AL: "BRAGG GRATINGS IN AN ACRYLATE POLYMER CONSISTING OF PERIODIC POLYMER-DISPERSED LIQUID-CRYSTAL PLANES" CHEMISTRY OF MATERIALS,US,AMERICAN CHEMICAL SOCIETY, WASHINGTON, vol. 5, no. 10, 31 December 1993 (1993-12-31), page 1533-1538 XP000674620 ISSN: 0897-4756 cited in the application page 1538, column 1	1-5
A	SUTHERLAND R L ET AL: "SWITCHABLE HOLOGRAMS IN NEW PHOTOPOLYMER-LIQUID CRYSTAL COMPOSITE MATERIALS" PROCEEDINGS OF THE SPIE, vol. 2404, 31 December 1995 (1995-12-31), pages 132-143, XP000863659 cited in the application page 138 -page 139	1-5

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 99/24158

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		AU 4041597 A	20-02-1998
		EP 0958329 A	24-11-1999
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